Pseudospin-mediated Atomic-scale Vortices and Their Quantum Interferences in Monolayer Graphene

Yu Zhang, Lin He†
Center for Advanced Quantum Studies, Department of Physics, Beijing Normal University, Beijing, 100875, People’s Republic of China
†Correspondence and requests for materials should be addressed to Lin He (e-mail: helin@bnu.edu.cn).

Vortex is a universal and significant phenomenon that has been known for centuries. However, creating vortices to the atomic limit has remained elusive because that the characteristic length to support a vortex is usually much larger than the atomic scale. Here, we demonstrate that pseudospin in graphene can help us to overcome this limitation and a single carbon defect in monolayer graphene is a pseudospin-mediated atomic-scale vortex. Using a plane wave to interfere with the vortex, we can obtain wavefront dislocations that directly reflect its topological and chiral features. In our experiments, \( N = 2 \) and -2 additional wavefronts are observed for the single carbon defects at A and B sublattices of graphene, demonstrating that they are atomic-scale vortices with angular momenta \( l = 2 \) and -2, respectively. Quantum interferences of two atomic-scale vortices with the same (or opposite) angular momentum are systematically studied with respect to their distances. Our result highlights the way to tailor the atomic-scale vortex in systems with pseudospin degree of freedom.
Vortex is familiar to us because of the classical version, such as water vortex and hurricane vortex, and it is now recognized as a universal and significant phenomenon in various fields, such as fluid physics, nonlinear optics, Bose–Einstein condensates, and condensed matter physics \([1-10]\). Recently, many attempts have been devoted to realize magnetic vortices based on the electronic spin in magnetic materials \([11-18]\). In the magnetic vortex, the spin changes its direction along a closed path surrounding the core, therefore, it is difficult to reduce the size of magnetic vortices to atomic scale because change of the spin direction at such a length scale will dramatically increase the energy of the system \([11-18]\). For electrons in graphene, besides the real electronic spin, there is an additional degree of freedom, sublattice pseudospin, that arises from the unique bipartite honeycomb lattice structure of graphene \([19-23]\). It is easy to change the direction of the pseudospin at atomic scale without cost energy of the system. Therefore, it is possible to realize pseudospin-mediated atomic-scale vortex in graphene.

In this Letter, we demonstrate that a single carbon defect can generate pseudospin-mediated atomic-scale vortex in monolayer graphene. Because the opposite chirality of the pseudospin texture of two different valleys of graphene, intervalley scattering induced by the single carbon defect leads to phase winding over a closed path surrounding the defect \([23]\), therefore, generating the pseudospin-mediated atomic-scale vortex. The bipartite lattice nature of graphene results in two types of atomic-scale vortices with opposite angular momentum. Quantum interferences of two atomic-scale vortices with the same (or opposite) angular momentum are systematically studied.

Generally, a topological vortex can be described as the phase winding of the wavefunction \(\psi(\mathbf{r}) = f(\mathbf{r})e^{il\varphi_\mathbf{r}}\) surrounding a phase singularity with zero wavefunction \(f(\mathbf{r}_0) = 0\). Here \(\varphi_\mathbf{r}\) represents the azimuthal angle and \(l\) is the angular momentum, representing the times of wavefunction rotates (winding number) when \(\varphi_\mathbf{r}\) undergoes a closed trajectory. Figures 1(a) and 1(b) show vectors of the wavefunction for the \(l = +2\) and \(-2\) vortices, respectively. The + (-) donates counterclockwise (clockwise) circulation, i.e., the chirality of the vortices. Since the topological and chiral features of vortex cannot be directly imaged, a proposal to capture the features of vortex via the interference has been widely adopted \([24]\). By introducing a plane wave that
propagates downward, there are $N = l = \pm 2$ additional wavefronts in the interference patterns, as shown in Figs. 1(c) and 1(d). The number of additional wavefronts $|N| = 2$ indicates the angular momentum of the vortex, and the appearance of the additional wavefronts behind or ahead the vortex can directly reflect the chirality, + or -, of the vortex. Therefore, the topological and chiral features of the vortex are measurable via the interference patterns [25-28]. Our low-energy continuum model calculations reveal that the single carbon defect at A and B sublattices of graphene, as shown in Figs. 1(e) and 1(f), also can generate $N = l = \pm 2$ additional wavefronts in the modulated charge densities for a selected direction of the intervalley scattering, as shown in Figs. 1(g) and 1(h) (see Supplemental Material for more details [29]). As shown in Figs. 1(i), the elastic intervalley scattering induced by the single carbon defect rotates the pseudospin by $\pm 2\theta_q$ ($\theta_q$ is the incident angle of electrons with momentum $q$) [30-34] and an accumulation of the phase shift over a closed path enclosing the single carbon defect is $\pm \int_0^{2\pi} 2d\theta_q = \pm 4\pi$ [34]. Such an effect leads to $N = \pm 2$ additional wavefronts in the modulated charge densities because that each additional wavefront contributes $2\pi$ in the phase shift. Therefore, the single carbon defect at A or B sublattice in monolayer graphene should be regarded as a phase singularity that is responsible for the generation of the $l = +2$ or $l = -2$ atomic-scale vortex. The pseudospin-mediated atomic-scale vortex nature of the single carbon defect in graphene should be well uncovered from the quantum interference of the defect-induced intervalley scattering.

To explore the atomic-scale vortex nature of the single carbon defects, we carried out scanning tunneling microscopy (STM) measurements. At a given STM tip position, the charge densities are governed by the interference of the electronic waves between electrons in the tip pointing towards the single carbon defect and their reflection from the defect by coupling a phase shift [34]. Meanwhile, the STM tip can probe the local density of states (LDOS) of electrons with high spatial resolution [35,36]. Therefore, we can obtain the interference patterns between a tip-introduced plane electronic wave and a defect-induced atomic-scale vortex from the STM images. In our experiments, we directly synthesized multilayer graphene with a high density of single carbon defects
on Ni foils using a facile chemical vapor deposition (CVD) method [38-40] (see methods and Fig. S1 of the Supplemental Material [29]). Usually, the topmost monolayer graphene is electronically decoupled from the underlying graphene sheets and behaves as a freestanding monolayer graphene due to the existence of large twist angles between them [39]. Such a result is demonstrated explicitly by measuring the well-defined Landau quantization of massless Dirac fermions in the topmost monolayer graphene, according to magnetic-field-dependent scanning tunneling spectroscopy (STS) spectra [41-43] (Fig. S2 of the Supplemental Material [29]).

Figures 2(a) and 2(b) show representative atomic STM images of monolayer graphene with a single carbon defect at the A and B sublattices, respectively. The characteristic Jahn-Teller distortion and distinctive topographic fingerprint of the triangular $\sqrt{3} \times \sqrt{3}$ R 30° interference patterns induced by the single carbon defect are clearly observed [38,39,44-46]. For the single carbon defects at the A and B sublattices, the tripod shapes in the STM images exhibit two different orientations (blue and green dotted outlines in Figs. 2(a) and 2(b)) due to the inversion symmetry with respect to the center of a C–C bond. The fast Fourier transform (FFT) analysis of the STM images are shown in Figs. 2(c) and 2(d), respectively. The outer bright spots connected by yellow dashed hexagon are the reciprocal lattice of monolayer graphene. At the center of the FFT images, a bright disk is observed, which is a significant feature of electronic properties in the monolayer graphene due to the forbidden intravalley backscattering [30-33]. The additional inner bright spots at the corners of Brillouin zone connected by green dashed hexagon are generated by the defect-induced intervalley scattering [30-33]. To explore the quantum interference of the intervalley scattering induced by the single carbon defect in monolayer graphene, we carry out the FFT-filtered analysis to obtain the modulation of charge densities due to the intervalley interference. Figures 2(e) and 2(f) show the FFT-filtered STM images along the directions of intervalley scattering enclosed by the white circles in Figs. 2(c) and 2(d), respectively. A clear signature of $N = +2$ and -2 additional wavefronts are observed for the single carbon defects at the A and B sublattices of monolayer graphene respectively,
which are well consistent with our theoretical calculations shown in Fig. 1. Very recently, similar experimental phenomenon has also been observed in H-chemisorbed monolayer graphene [34]. In our experiment, the same features are also observed for the defect-induced intervalley scattering in three directions related by a $C_3$ rotation in both the STM images and STS maps, and the result is robust under different experimental conditions such as the applied bias voltages, tunneling currents, and rotation of the scanning angles (Figs. S3-S5 of the Supplemental Material [29]). Therefore, the robust $N = +2$ and -2 additional wavefronts demonstrate that the generation of the $l = +2$ and -2 atomic-scale vortices around the single carbon defect at the A and B sublattices of monolayer graphene, respectively.

Now we begin to explore the quantum interferences between two pseudospin-mediated atomic-scale vortices in monolayer graphene. Figure 3 summarizes the interferences of two atomic-scale vortices with the same chirality (the same angular momentum), which are realized by two individual single carbon defects at the same sublattice. As shown in Figs. 3(a) and 3(b), two individual single carbon defects with different distances are at the same sublattice (A sublattice), which can be inferred from the orientations of the tripod shapes. When the distance between the two single carbon defects is relatively large, i.e., $d = 17.0$ nm (Fig. 3(a)), the two atomic-scale vortices are almost isolated and the interferences between them are negligible. Therefore, the $N = 2$ additional wavefronts are observed around each defect, as marked by black dotted lines in Fig. 3(c). With decreasing the distance between the two single carbon defects to $d = 2.7$ nm (Fig. 3(b)), the interferences between the two atomic-scale vortices become important. Then the two defects totally contribute to $N = 2$ additional wavefronts together (Fig. 3(d)). Obviously, the number of additional wavefronts shows great dependence on the distance $d$ between the two individual single carbon defects, which can be well captured by the quantum interferences between two $l = 2$ vortices. Figures 3(e) and 3(f) show the vector diagrams of the two $l = 2$ vortices centered at the blue dots and their interference with a plane wave propagating downward. When the two vortices are far from each other, the structure of each vortex shows a little deformation, but still keeps a complete $l = 2$ angular momentum surrounding each of them. Therefore,
the $N = 2$ additional wavefronts are expected to appear around each vortex, as simulated in Fig. 3(e). However, when the two vortices are quite close, their structures are strongly disturbed and the two vortices prefer to superimpose into a new vortex with $l = 2$. Therefore, the total additional wavefronts of the two coupled vortices are still $N = 2$ in the interference patterns (Fig. 3(f)). Obviously, the theoretical results based on the interferences of two vortices are well consistent with our experiments.

Figure 4 summarizes the interferences of two atomic-scale vortices with the opposite chirality, which are realized by two individual single carbon defects at different sublattices of graphene. Figures 4(a) and 4(b) show typical STM images of two individual single carbon defects with different distances located at the A and B sublattices, as revealed by the inverse orientations of the tripod shape. When the separation between the two defects is $d = 8.8$ nm (Fig. 4(a)), the interferences between them are negligible and $N = +2$ and -2 additional wavefronts are observed around the single carbon defects at the A and B sublattices respectively (Fig. 4(c)). However, for $d = 1.0$ nm (Fig. 4(b)), the interferences between the two atomic-scale vortices with the opposite chirality result in zero additional wavefront as a whole (Fig. 4(d)). The above experimental result can be well captured by the quantum interferences between a $l = 2$ vortex and a $l = -2$ vortex (antivortex). For a larger separation $d$, the vortices roughly maintain the pristine structure and generate the separated $N = 2$ and -2 additional wavefronts when they interfere with a plane wave propagating downward (Fig. 4(e)). However, for a smaller $d$, the winding structures of a vortex and an antivortex are mutually offset, leading to the annihilation of vortex-antivortex pair and the irrotational phase structures as a whole. Therefore, no additional wavefront can be observed (Fig. 4(f)). More strictly calculations of two single carbon defects at the same sublattice and at different sublattice of graphene based on the low-energy continuum model in the framework of a $T$-matrix approach are given in the Supplemental Material [29], which also reproduce well the main features observed in our experiment (Figures 3 and 4).

In summary, we demonstrate that the individual single carbon defect at the A and B sublattice of monolayer graphene can be regarded as the pseudospin-mediated atomic-scale vortex with the angular momentum $l = +2$ and -2, respectively. The interferences
of the pseudospin-mediated vortex-vortex and vortex-antivortex pairs with respect to their distances are studied. When the two defects are far away, the two vortices associated with the defects are isolated and each of them shows two additional wavefronts. When the two defects are close, the two vortices are interacted and show two additional wavefronts for a vortex-vortex pair and zero additional wavefront for a vortex-antivortex pair.

**Acknowledgements**

This work was supported by the National Natural Science Foundation of China (Grant Nos. 11974050, 11674029). L.H. also acknowledges support from the National Program for Support of Top-notch Young Professionals, support from “the Fundamental Research Funds for the Central Universities”, and support from “Chang Jiang Scholars Program”.
References

1. M. Berry, Making waves in physics. Nature 403, 21 (2000).
2. T. Shinjo, T. Okuno, R. Hassdorf, et al. Magnetic Vortex Core Observation in Circular Dots of Permalloy. Science 289, 930-932 (2000).
3. V. F. Mitrovic, E. E. Sigmund, M. Eschrig, et al. Spatially resolved electronic structure inside and outside the vortex cores of a high-temperature superconductor. Nature 413, 501-504 (2001).
4. A. K. Yadav, C. T. Nelson, S. L. Hsu, et al, Observation of polar vortices in oxide superlattices. Nature 530, 198-201 (2016).
5. J. Bardeen, M. J. Stephen, Theory of the Motion of Vortices in Superconductors. Phys. Rev. 140, A1197-A1207 (1965).
6. E. K. Dahl, E. Babaev, and A. Sudbø, Unusual States of Vortex Matter in Mixtures of Bose-Einstein Condensates on Rotating Optical Lattices. Phys. Rev. Lett. 101, 255301 (2008).
7. H. Li, J. R. Friend, and L. Y. Yeo, Microfluidic Colloidal Island Formation and Erasure Induced by Surface Acoustic Wave Radiation. Phys. Rev. Lett. 101, 084502 (2008).
8. D. R. Nelson, V. M. Vinokur, Boson localization and correlated pinning of superconducting vortex arrays, Phys. Rev. B 48, 13060-13097 (1993).
9. M. R. Matthews, B. P. Anderson, P. C. Haljan, et al, Vortices in a Bose-Einstein Condensate. Phys. Rev. Lett. 83, 2498 (1999).
10. M. V. Berry, R. G. Chambers, M. D. Large, C. Upstill, J. C. Walmsley, Wavefront dislocations in the Aharonov-Bohm effect and its water wave analogue. Eur. J. Phys. 1, 154 (1980).
11. T. Kurumaji, T. Nakajima, M. Hirschberger, A. Kikkawa, Y. Yamasaki, H. Sagayama, H. Nakao, Y. Taguchi, T. Arima1, Y. Tokura, Skyrmion lattice with a giant topological Hall effect in a frustrated triangular-lattice magnet. Science 365, 914–918 (2019).
12. L. Caretta, M. Mann, F. Büttner, K. Ueda, B. Pfau, C. M. Günther, P. Hessing, A.
Churikova, C. Klose, M. Schneider, D. Engel, C. Marcus, D. Bono, K. Bagschik, S. Eisebitt, and G. S. D. Beach, Fast current-driven domain walls and small skyrmions in a compensated ferrimagnet. *Nat. Nanotechnol.* **13**, 1154-1160 (2018).

13. L. Wang, Q. Feng, Y. Kim, R. Kim, K. H. Lee, S. D. Pollard, Y. J. Shin, H. Zhou, W. Peng, D. Lee, W. Meng, H. Yang, J. H. Han, M. Kim, Q. Lu, and T. W. Noh, Ferroelectrically tunable magnetic skyrmions in ultrathin oxide heterostructures. *Nat. Mater.* **17**, 1087-1094 (2018).

14. N. Romming, A. Kubetzka, C. Hanneken, K. von Bergmann, and R. Wiesendanger, Field-Dependent Size and Shape of Single Magnetic Skyrmions. *Phys. Rev. Lett.* **114**, 177203 (2015).

15. H. S. Park, X. Yu, S. Aizawa, T. Tanigaki, T. Akashi, Y. Takahashi, T. Matsuda, N. Kanazawa, Y. Onose, D. Shindo, A. Tonomura, and Y. Tokura, Observation of the magnetic flux and three-dimensional structure of skyrmion lattices by electron holography. *Nat. Nanotechnol.* **9**, 337-342 (2014).

16. S. Heinze, K. von Bergmann, M. Menzel, J. Brede, A. Kubetzka, R. Wiesendanger, G. Bihlmayer, and S. Blügel, Spontaneous atomic-scale magnetic skyrmion lattice in two dimensions. *Nat. Phys.* **7**, 713-718 (2011).

17. X. Z. Yu, Y. Onose, N. Kanazawa, J. H. Park, J. H. Han, Y. Matsui, N. Nagaosa, and Y. Tokura, Real-space observation of a two-dimensional skyrmion crystal. *Nature* **465**, 901-904 (2010).

18. S. Mühlbauer, B. Binz, F. Jonietz, C. Pfleiderer, A. Rosch, A. Neubauer, R. Georgii, P. Böni, Skyrmion Lattice in a Chiral Magnet. *Science* **323**, 915-919 (2009).

19. D. Xiao, W. Yao, and Q. Niu, Valley-Contrasting Physics in Graphene: Magnetic Moment and Topological Transport. *Phys. Rev. Lett.* **99**, 236809 (2007).

20. M. Mecklenburg, B. Regan, Spin and the Honeycomb Lattice: Lessons from Graphene. *Phys. Rev. Lett.* **106**, 116803 (2011).

21. D. R. Gulevich, D. Yudin, Mimicking graphene with polaritonic spin vortices. *Phys. Rev. B* **96**, 115433 (2017).

22. D. Song, V. Paltoglou, S. Liu, *et al.* Unveiling pseudospin and angular momentum in photonic graphene. *Nat. Commun.* **6**, 6272 (2015).
23. P. Mallet, I. Brihuega, S. Bose, *et al*. Role of pseudospin in quasiparticle interferences in epitaxial graphene probed by high-resolution scanning tunneling microscopy. *Phys. Rev. B* **86**, 045444 (2012).

24. J. F. Nye, M. V. Berry, Dislocations in wave trains. *Proc. R. Soc. Lond. A.* **336**, 165-190 (1974).

25. Y. Yang, W. Wang, P. Moitra, I. I. Kravchenko, D. P. Briggs, J. Valentine, Dielectric Meta-Reflectarray for Broadband Linear Polarization Conversion and Optical Vortex Generation. *Nano Lett.* **14**, 1394–1399 (2014).

26. M. Rafayelyan, E. Brasselet, Bragg-Berry mirrors: reflective broadband q-plates. *Opt. Lett.* **41**, 3972-3975 (2016).

27. J. Lu, C. Qiu, M. Ke, Z. Liu, Valley Vortex States in Sonic Crystals. *Phys. Rev. Lett.* **116**, 093901 (2016).

28. Y. Zhang, Y. Su, L. He, Intervally quantum interference and measurement of Berry phase in bilayer graphene. arXiv: 2005.00958.

29. See Supplemental Material for methods, more STM images, STS spectra, and details of the theoretical analysis.

30. G. M. Rutter, J. N. Crain, N. P. Guisinger, *et al*. Scattering and Interference in Epitaxial Graphene. *Science* **317**, 219-222 (2007).

31. C. Bena, Effect of a Single Localized Impurity on the Local Density of States in Monolayer and Bilayer Graphene. *Phys. Rev. Lett.* **100**, 076601 (2008).

32. I. Brihuega, P. Mallet, C. Bena, *et al*. Quasiparticle Chirality in Epitaxial Graphene Probed at the Nanometer Scale. *Phys. Rev. Lett.* **101**, 206802 (2008).

33. C. Dutreix, M. I. Katsnelson, Friedel oscillations at the surfaces of rhombohedral N-layer graphene. *Phys. Rev. B* **93**, 035413 (2016).

34. C. Dutreix, H. González-Herrero, I. Brihuega, *et al*. Measuring the Berry phase of graphene from wavefront dislocations in Friedel oscillations. *Nature* **574**, 219–222 (2019).

35. M. F. Crommie, C. P. Lutz, D. M. Eigler, Imaging standing waves in a two-dimensional electron gas. *Nature* **363**, 524-527 (1993).

36. P. T. Sprunger, L. Petersen, E. W. Plummer, *et al*. Giant Friedel Oscillations on the
37. Y. Zhang, Q. Guo, S. Li, and L. He, Nanoscale probing of broken-symmetry states in graphene induced by individual atomic impurities, *Phys. Rev. B* **101**, 155424 (2020).

38. Y. Zhang, F. Gao, S. Gao, L. He, Tunable magnetism of a single-carbon vacancy in graphene. *Sci. Bull.* **65**, 194–200 (2020).

39. Y. Zhang, S. Li, H. Huang, *et al.* Scanning Tunneling Microscopy of the $\pi$ Magnetism of a Single Carbon Vacancy in Graphene. *Phys. Rev. Lett.* **117**, 166801 (2016).

40. H. Yan, C. Liu, K. Bai, *et al.* Electronic structures of graphene layers on a metal foil: the effect of atomic-scale defects, *Appl. Phys. Lett.* **103**, 143120 (2013).

41. D. L. Miller, K. D. Kubista, G. M. Rutter, *et al.* Observing the Quantization of Zero Mass Carriers in Graphene. *Science* **324**, 924-927 (2009).

42. M. O. Goerbig, Electronic properties of graphene in a strong magnetic field. *Rev. Mod. Phys.* **83**, 1193-1243 (2011).

43. L. Yin, S. Li, J. Qiao, *et al.* Landau quantization in graphene monolayer, Bernal bilayer, and Bernal trilayer on graphite surface. *Phys. Rev. B* **91**, 115405 (2015).

44. M. M. Ugeda, I. Brihuega, F. Guinea, J. M. Gomez-Rodriguez, Missing Atom as a Source of Carbon Magnetism. *Phys. Rev. Lett.* **104**, 096804 (2010).

45. J. Mao, Y. Jiang, D. Moldovan, *et al.* Realization of a tunable artificial atom at a supercritically charged vacancy in graphene. *Nat. Phys.* **12**, 545-549 (2016).

46. Y. Jiang, P. Lo, D. May, *et al.* Inducing Kondo screening of vacancy magnetic moments in graphene with gating and local curvature. *Nat. Commun.* **9**, 2349 (2018).
**Figures**

(a) \( l = 2 \) (b) \( l = -2 \)

(c) \( N = 2 \) (d) \( N = -2 \)

**Figure 1.** Schematic diagrams of vortex and its interference with a plane wave. (a,b) The vectors of wavefunction for \( l = \pm 2 \) vortices. The center of vortices is marked by blue or green dots. (c,d) Interference patterns between a vortex and a vortex-free plane wave that propagates downward. The additional wavefronts are marked by black dashed lines. The pseudospin rotates by \( \pm 2\theta_q \). (e,f) Atomic structures of a single carbon defect at A and B sublattices, respectively. (g,h) Low energy continuum model calculations of the charge density oscillations due to the intervalley scattering in monolayer graphene with a single carbon defect at A and B sublattices, respectively. (i) The process of quasiparticles scattering from a given valley \( K' \) (\( K \)) to a nearest valley \( K \) (\( K' \)) in graphene.
Figure 2. The single carbon defect induced wavefront dislocations in monolayer graphene. (a,b) The topography STM images of an individual single carbon defect in monolayer graphene (\(V_b = 200 \text{ mV}, I = 300 \text{ pA}\)). The single carbon defect induced triangular interference patterns are marked by blue and green dotted outlines, which are related to the single carbon defect at the A and B sublattices, respectively. The atomic structures are given in the insets. (c,d) FFT of the STM images in (a) and (b), respectively. The outer hexagonal spots (corners of the yellow dotted line) and inner bright spots (corners of the green dotted line) correspond to the reciprocal lattice of graphene and the interference of the intervalley scattering, respectively. (e,f) FFT-filtered images of (a) and (b) along the direction indicated by white circles in (c) and (d). The black dashed lines correspond to \(N = \pm 2\) additional wavefronts.
Figure 3. The interference of vortices and wavefront dislocations induced by two single carbon defects at the same sublattice of monolayer graphene. (a,b) Typical STM images of two individual single carbon defects at the same sublattice (A sublattice) of monolayer graphene with the separated distances of (a) 17.0 nm and (b) 2.7 nm, respectively. The dotted tripod shapes are added manually to indicate the orientation and position of the defects. (c,d) FFT-filtered images of (a) and (b) along the marked direction of intervalley scattering. The additional wavefronts are marked by black dashed lines. Inset: the filters applied in the Fourier space. (e,f) Up panels: the structures of interference between two \( l = 2 \) vortices with different separations. Bottom panels: The interference patterns between two vortices and a plane wave propagating downward. The numbers of additional wavefronts are marked in the figures.
Figure 4. The interference of vortices and wavefront dislocations induced by two single carbon defects at the different sublattices of monolayer graphene. (a,b) Typical STM images of two individual single carbon defects at A and B sublattices of monolayer graphene with the separated distances of (a) 8.8 nm and (b) 1.0 nm, respectively. The dotted tripod shapes are added manually to indicate the orientation and position of the defects. (c,d) FFT-filtered images of (a) and (b) along the marked direction of intervalley scattering. The additional wavefronts are marked by black dashed lines. Inset: the filters applied in the Fourier space. (e,f) Up panels: the structures of interference between a $l = 2$ and a $l = -2$ vortices with different separations. Bottom panels: The interference patterns between two vortices and a plane wave propagating downward. The additional wavefronts are marked in the figures.