Evidence of flat bands and correlated states in buckled graphene superlattices

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Two-dimensional atomic crystals can radically change their properties in response to external influences, such as substrate orientation or strain, forming materials with novel electronic structure. A prime example is the creation of weakly dispersive, ‘flat’ bands in bilayer graphene for certain ‘magic’ angles of twist between the orientations of the two layers. The quenched kinetic energy in these flat bands promotes electron–electron interactions and facilitates the emergence of strongly correlated phases, such as superconductivity and correlated insulators. However, the very accurate fine-tuning required to obtain the magic angle in twisted-bilayer graphene poses challenges to fabrication and scalability. Here we present an alternative route to creating flat bands that does not involve fine-tuning. Using scanning tunnelling microscopy and spectroscopy, together with numerical simulations, we demonstrate that graphene monolayers placed on an atomically flat substrate can be forced to undergo a buckling transition, resulting in a periodically modulated pseudo-magnetic field, which in turn creates a ‘post-graphene’ material with flat electronic bands. When we introduce the Fermi level into these flat bands using electrostatic doping, we observe a pseudogap-like depletion in the density of states, which signals the emergence of a correlated state. This buckling of two-dimensional crystals offers a strategy for creating other superlattice systems and, in particular, for exploring interaction phenomena characteristic of flat bands.

Flat bands facilitate the emergence of strongly correlated electronic phases. A celebrated example is the Landau-level (LL) sequence of magnetically induced flat bands that can host correlated phases, such as fractional quantum-Hall states or magnetically induced Wigner crystals. Magnetically induced flat bands, however, have limited applicability because the broken time-reversal symmetry precludes the emergence of certain correlated states, such as superconductivity. More recently, twisted bilayer graphene that is finely tuned to a magic angle where a flat band emerges has introduced a new platform for the creation of correlated phases.

Here we explore an alternative path to flat bands that does not require fine-tuning or breaking time-reversal symmetry. The strategy involves creating flat bands by using the band-structure reconstruction that occurs when a two-dimensional (2D) membrane undergoes a buckling transition. Buckling transitions in stiff membranes are typically triggered by in-plane compressive strain that can be generated during thermal cycling, by solvent-induced capillary forces, or by substrate-induced stress. On exceeding a critical strain value, buckling of the membrane reduces its elastic energy through out-of-plane distortions, resulting in intriguing periodic strain patterns whose structures are dictated by boundary conditions and strain distribution. We find that in graphene, buckling-induced strain arrays give rise to a periodic pseudo-magnetic field (PMF), which reconstructs the low-energy band structure into a series of essentially flat bands. Unlike earlier realizations of PMF that were mostly local in nature, the buckling transitions studied here produce a global change in the electronic structure, which comprises a sequence of flat bands that percolate throughout the material.

We employed the thermally induced buckling transition in graphene deposited on NbSe2 or hexagonal boron nitride substrates to create a periodic PMF. The buckling structures studied here are typically nested between ridges (Extended Data Fig. 1) that often form in graphene during fabrication. Topographical analysis suggests that the buckling is triggered by compressive strain generated by the collapse of ridges during thermal cycling (see Methods section ‘Sample preparation’). This produces various buckling patterns, from 1D to 2D, with similar nanometre-scale periods (Fig. 1b, c), suggesting a universal buckling mechanism that is insensitive to the lattice mismatch between graphene and its substrate.

In Fig. 1a we show a schematic of the sample and scanning tunnelling microscopy (STM) measurement set-up. The topography of a buckling-induced triangular superstructure in graphene deposited on NbSe2 is shown in Fig. 1b, right panel. This superlattice consists of alternating crests and troughs (bright and dark, respectively; Fig. 2a) with...

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0.17-nm height modulation and period $a_b = 14.4 \pm 0.5$ nm. The large lattice mismatch between graphene (0.246 nm) and NbSe$_2$ (0.36 nm) rules out a moiré pattern interpretation (Methods). We first focus on the electronic structure obtained from the $dV/dI$ spectra ($I$ is the current, $V$ is the bias) in the crest regions (Fig. 2b). The spectra comprise a sequence of peaks identified as PMF-induced pseudo-Landau levels (PLLs) renormalized by the PMF superlattices. The energy of the most pronounced peak (labelled $N = 0$) is aligned with the charge neutrality point (CNP) as determined from the spectra taken in the non-buckled area (Extended Data Fig. 2a). The CNP energy, $E_{\text{CNP}}$, is shifted to about 0.5 eV above the Fermi level, owing to the hole doping induced by the NbSe$_2$ substrate. Starting from the $N = 0$ PLL, which coincides with $E_{\text{CNP}}$, we label the remaining PLLs in order of increasing (decreasing for the hole sector, $N < 0$) energies as $N = \pm 1$, $\pm 2$, and we find that they follow the sequence expected of LLs in flat monolayer graphene, $E_N = E_0 + \text{sgn}(N)\nu F $. (here $e$ is the electron charge and $\hbar = h/(2\pi)$ is the reduced Planck constant. This PLL sequence confirms the existence of a PMF in the buckled graphene membrane. Using the Fermi-velocity value of unbuckled graphene, $v_F = 1.0 \times 10^{6}$ m s$^{-1}$, we estimate the value of the PMF in the centre of the crest region as $B_{\text{PMF}} = 108 \pm 8$ T (Fig. 2b, right inset). Outside the buckled region, where the STM topography is flat, the spectrum exhibits a featureless ‘V’-shape, as expected of unstrained graphene on NbSe$_2$, with the minimum at $E_0 = 0.5$ eV (Extended Data Fig. 2).

Another hallmark of a PMF is the sublattice polarization of the electronic wavefunction in the $N = 0$ level. This means that for a given PMF sign, the $N = 0$ electronic wavefunction is localized on one sublattice, while for the opposite sign PMF it resides on the other sublattice. The PMF-induced sublattice polarization, which is the counterpart of the magnetically induced valley polarization of the $N = 0$ level, follows directly from the opposite signs of the PMF in the K and K' valleys. The observation of sublattice polarization in the atomic-resolution STM images shown in Fig. 2d–f (see below) thus provides a direct experimental signature of the extent PMF in buckled graphene superstructures.
sequence obtained for $B_{\text{eff}} = 112 \, \text{T} (\beta = 120 \, \text{T})$ matches the experimentally measured sequence shown in Fig. 2b.

Figure 3a–c plots the evolution of the calculated local density of states (LDOS) with PMF amplitude, for each sublattice in the crest, transition and trough regions. In the crest and trough regions, we observe a strong imbalance in low-energy LDOS intensity between the A and B sublattices (Fig. 3a, c), which is absent in the intermediate transition region (Fig. 3b). This is consistent with the experimentally observed sublattice polarization in the crest (Fig. 2e) and trough regions (Fig. 2f), and with its absence in the transition region (Fig. 2d). In Fig. 3e we show the simulated LDOS spectrum in the crest region for $B_{\text{eff}} = 112 \, \text{T}$, together with a fit to the square-root dependence on $N$, which is consistent with the experimentally measured spectra shown in Fig. 2b as discussed in Extended Data Fig. 6. The simulated LDOS spectrum in the trough region (Fig. 3f) is approximately linear in $N$ with a level spacing of about 90 meV, consistent with the experimental results in Fig. 2c. To elucidate the origin of this linear peak sequence, we show in Fig. 3g the evolution of the LDOS calculated along a path connecting two crests (arrow in Fig. 3d, lower panel). The experimental peak positions in the crest (trough) regions are shown by right-pointing (left-pointing) arrows, respectively. In the centre of the trough the equidistant level sequence is clearly seen. We note that these levels are not solely determined by the local value of the PMF and they do not exhibit spatial dispersion. Furthermore, although these states spread into the crest regions, they disappear on approaching the PLLs in the crest centre. The discrete nature of these equidistant levels indicates that they originate from strain-induced confinement within the quantum well defined by the PMF, closely resembling magnetic confinement in quantum dots in 2D semiconductors. As in the case of quantum dots, here the electrons are trapped in a PMF-induced potential well, which produces a set of levels spaced by a characteristic (geometry-dependent) energy scale $\Delta E = h v_{\text{B}} \Delta W$, where $W$ is the dot size. Using the energy scale of the levels in the troughs, approximately 90 meV, we estimate $W = 21 \, \text{nm}$, which is approximately the size of the well indicated by the grey dashed lines in Fig. 3g, lower panel. In the troughs, the energy of each level decreases with increasing PMF (Fig. 3c) until all levels merge into one degenerate level that approaches the CNP when the magnetic length becomes considerably smaller than the dot size.

We next discuss the emergence of flat bands in this system. The periodic potential imposed by the PMF superlattice breaks up the low-energy conical band of graphene into a series of mini-bands whose width is controlled by the strength of the PMF amplitude, $B$. At low values of $B$, the minibands restructure the LDOS into a series of semi-discrete levels, as illustrated in Extended Data Fig. 7. As $B$ increases, these levels evolve into increasingly narrower bands that become flat in the limit of large $B$. In Fig. 4a, we plot the first few minibands in the buckled graphene $G$/NbSe$_2$ sample for $B_{\text{eff}} = 112 \, \text{T}$. They all show flat-band segments along the $K'–M'$ line in the mini-Brillouin zone. The corresponding simulated LDOS contours in the three minibands with energies $E_0 - E_a = -0.03 \, \text{eV}$, $E_1 - E_a = -0.17 \, \text{eV}$ and $E_2 - E_a = -0.28 \, \text{eV}$, shown in Fig. 4b, show good agreement with the measured $dI/dV$ maps in Fig. 4c, indicating that the model captures the salient features of the data. This sequence of buckling-induced flat bands that are well separated from each other would be ideally suited for hosting correlated electronic states, if it were possible to align the Fermi energy within one of the flat bands. However, this was not possible in the buckled $G$/NbSe$_2$ sample, because of the finite conductance of the NbSe$_2$ substrate. Nevertheless, our observations indicate that this could be achieved by creating...
a buckling pattern in graphene deposited on an insulating substrate, as shown below.

In order to study correlation effects in buckling-induced flat bands, we turn to the G/hBN sample. In this case, applying a gate voltage across the insulating hBN layer allows us to bring the Fermi level within the flat band. Using the same sample preparation process as for the G/NbSe₂ sample, we again obtain buckling superlattices as illustrated in Fig. 5a, b.

The gate-voltage dependence of the dI/dV spectra of the G/hBN sample in the transition region where the strain is minimal (Fig. 5c) shows that for \( V_g = 0 \) the spectrum is V-shaped and that its minimum, which marks the CNP, is aligned with the Fermi level. This indicates that, unlike the case of G/NbSe₂, the G/hBN sample is not doped by the hBN substrate. Tuning the gate voltage from \(-62 \) V to \(+38 \) V gradually moves the CNP from the hole-doped (about \(-100 \) mV) to the electron-doped sector (about \(+200 \) mV) in Fig. 5c. In Fig. 5d we compare the dI/dV spectra in the crest and transition regions for the heavily hole-doped (\( V_g = -62 \) V) case. Here, the crest spectrum features a prominent peak at the CNP that is flanked by a sequence of weaker peaks (blue arrows), closely resembling the crest spectrum in the G/NbSe₂ sample (Fig. 2b). As before, we identify the prominent peak with the strain-induced N=0 PLL, and fitting the peak sequence with a square-root level-index dependence, we obtain the PMF value \( B_{\text{eff}} = 104 \) T (Fig. 5d inset) consistent with the simulations described in Extended Data Fig. 9. Changing the backgate voltage from the hole-doped (\( V_g = -62 \) V) to the electron-doped (\( V_g = +38 \) V) sector (Fig. 5e) we note that the N=0 PLL tracks the CNP. As before the N=0 PLL corresponds to a buckling-induced weakly dispersive flat band. When doping the sample to partially fill this band, a pseudo-gap feature at the Fermi level splits the peak in two, indicating the appearance of a correlation-induced state. Labelling the peaks above and below the Fermi level as upper band and lower band, respectively, we find that when the Fermi level is aligned with the CNP, the upper- and lower-band peaks have equal intensities. Doping away from charge neutrality, we observe a pronounced spectral weight redistribution between the two peaks, so that in the electron-doped regime (\( V_g > 0 \)) the intensity of the lower band dominates that of the upper band, whereas in the hole-doped regime (\( V_g < 0 \)) the upper-band intensity becomes dominant. The appearance of the pseudo-gap feature and the spectral weight redistribution in the partially filled flat band in the crest regions of buckled G/hBN is strikingly similar to that observed in the partially filled flat band of magic-angle twisted bilayer graphene \(^{15-17}\), where correlation-induced insulating and superconducting states have been observed.

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**Fig. 3** Simulated LDOS in buckled graphene. a–c. Simulated evolution of the LDOS with energy (\( E \)) and PMF amplitude (\( B \) as defined in equation (1)) in the crest (a), transition (b) and trough (c) regions. Upper (lower) panels represent the A (B) sublattice. The colour scale represents the LDOS intensity. d. Upper panel, STM topography (\( V = +500 \) mV, \( I = 20 \) pA) showing the triangular superlattice with alternating crest (red) and trough (blue) regions. Lower panel, PMF configuration used in the simulation. The colour scale represents the PMF amplitude \( B \) (see equation (1)). The symbols indicate the positions of the calculated LDSOS in a–c, and the green line indicates the calculated path for g, e, f. Upper panels, calculated LDOS as a function of energy \( E \) in the crest and trough regions for \( B_{\text{eff}} = 112 \) T (\( B = 120 \) T). Lower panels, level-index dependence of the simulated (black squares) and experimental (red dots) peak energy levels, measured relative to the charge neutrality point, \( E - E_F \). The red line represents a fit to the experimental data. \( E_F = 0.43 \) eV is taken from the experimental data on an unbuckled region of the sample. g. Upper panel, contour plot of the LDOS spectra (sublattice averaged) as a function of energy (\( E \)) and position (\( x \)) connecting two crests along the green line in d. Green arrows indicate the positions of the peaks in the measured spectra shown in Fig. 2b (right-pointing arrows) and Fig. 2c (left-pointing arrows). The colour scale represents the LDOS intensity. Lower panel, evolution of the simulated value of \( B_{\text{eff}}/B \) along the green path in d.
These findings demonstrate that buckling-induced periodic strain patterns offer a new experimental strategy for the creation of flat bands and for inducing correlated states with exceptional flexibility. The shape, period and symmetry of the buckled structures can be controlled by experimentally adjustable parameters, such as boundary geometry and strain distribution, enabling the realization of flat bands with prescribed geometry. We believe that the described way of buckling 2D crystals will be used widely to create other superlattice systems with controllable electronic band structure, thereby enabling the exploration of strong interaction effects and the emergence of correlated phases.

Fig. 4 | Flat bands and LDOS maps. a, Calculated band structure for a buckled graphene superlattice with period $a_b = 14$ nm and PMF amplitude $B_{\text{eff}} = 112$ T ($B = 120$ T). Inset, superlattice mini-Brillouin zone, nested within the original Brillouin zone of flat graphene, together with the trajectory along which the band structure is calculated. b, c, Calculated LDOS contours (‘Theory’), b and measured $dI/dV$ maps (‘Experiment’, c) at $B_{\text{eff}} = 112$ T for the three energies $(E_0 - E_D, E_1 - E_D, E_2 - E_D)$ that correspond to the flat-band regions in a, as indicated by the colour-coded boxes.

Fig. 5 | Flat bands in buckled G/hBN. a, STM topography of the buckled G/hBN sample ($V_b = -300$ mV, $I = 20$ pA). b, Height profile along the black line in a shows the approximately 3.5 Å height modulation of the buckling pattern. The horizontal dashed lines demarcate the extent of the height modulation. c, Gate-voltage dependence of the spectra in the transition region shows the shift of the CNP (arrows) with doping ($V_b = -400$ mV, $I = 20$ pA). The black dashed line labels the Fermi level ($E_F$). d, $dI/dV$ spectra from the crest (blue trace) and transition (black trace) regions labelled respectively by the star and the circle in a ($V_b = -400$ mV, $I = 20$ pA). Inset, PLL energy in the crest area plotted against the square root of the LL index, $N = 0, \pm 1, \pm 2, \ldots$. e, Gate-voltage ($V_g$) dependence of the spectra in the crest region shows the pseudo-gap feature and spectral weight redistribution in the partially filled flat band ($V_b = -400$ mV, $I = 20$ pA).
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Methods

Sample preparation
To avoid oxygen and moisture contamination, the heterostructures are fabricated in a dry Ar atmosphere in a glovebox. Graphene is first exfoliated on a PMMA—poly (methyl methacrylate)—film and then transferred onto a thin NbSe$_2$ flake deposited on a SiO$_2$/Si substrate. Instead of dissolving the PMMA in acetone, we mechanically peeled it off. The Au electrodes were deposited by standard SEM lithography. Before loading the sample into the STM chamber, the sample is annealed at 230 °C in forming gas (10% H$_2$ and 90% Ar) overnight to remove the PMMA residue. The STM experiments are performed in a home-built STM at 4.6 K with a cut Pt$_{50}$Ir$_{50}$ tip, and the sample is located using a capacitive-based self-navigation technique. The tip used here is calibrated on the Au electrode, and the dI/dV curves are measured using a standard lock-in technique with a small a.c. voltage modulation (2 mV at 473.1 Hz) added to the d.c. junction bias.

Buckling pattern formation
Periodic pattern formation following a buckling transition is largely determined by the boundary conditions and stress distribution. In order to understand the buckling pattern in the G/NbSe$_2$ sample, we carried out large-area topography measurements that include the boundaries of the pattern (Extended Data Fig. 1). In Extended Data Fig. 1a, the triangular pattern is delimited by two intersecting ridges (labelled as ridge 1 and ridge 2; ~0.5 μm long and 4 nm tall) that form a 60° fan. Zooming into the fan area (Extended Data Fig. 1c), we discern the buckling pattern. In Extended Data Fig. 1c, d, we show that the period of the pattern increases monotonically with the distance from the apex where the two ridges meet.

When graphene is deposited on a substrate, folds, ridges and bubbles due to trapped gas or solvents are produced. Many of these defects disappear on annealing (see Methods section ‘Sample preparation’), but not all, presumably because their geometry is such that it does not allow the trapped species to escape or because the defect is pinned to the substrate. We observe that the ridges that survive the annealing step (Extended Data Fig. 1a) do not show the usual concave profile seen before annealing, but rather show evidence of collapse, probably due to freezing of the trapped gas that supported the ridge. Following the collapse, the ridge profile becomes convex and is flanked by two tall lips on the boundaries of the original fold (Extended Data Fig. 1e). The lip pointing inwards towards the fan area is consistently shorter than the outside lip, suggesting that some of the graphene membrane comprising the original fold was pushed inwards. This increases the area of the membrane trapped between the two ridges (ridges 1 and 2 in Extended Data Fig. 1a), resulting in biaxial compressive strain which can trigger the buckling transition. To test this scenario, we conjecture that the concave region of the ridge was originally part of the convex top.

This suggests that one can reconstruct the original shape by a mirror transformation of the concave part relative to the green dashed line in Extended Data Fig. 1e (the line intersects the tallest point of the convex part and is parallel to the substrate). This produces the reconstructed dome shown by the red symbols in Extended Data Fig. 1e.

Using this procedure immediately reveals a missing part of the original dome of length ΔL as indicated in the figure. The strain produced by this increased length is estimated from the ratio between ΔL and the bisection of the 60° triangle: \( \varepsilon = (\Delta L/L) \sin 30° = 2\Delta L/L, \) where \( L \) is the distance from the apex formed by the intersection of the two ridges (Extended Data Fig. 1f).

Theoretical models and simulations of wrinkling based on minimizing the energy of a stretched or compressed membrane by allowing out of plane distortions have shown that there are simple scaling laws relating the period of the buckled membrane \( \lambda \) to the strain \( \varepsilon \).

Using \( \varepsilon = 0.3 \) nm for the graphene thickness, \( \nu = 0.15 \) for its Poisson ratio and the expression for the strain as a function of distance \( L \), we find

\[
\lambda = \frac{4\pi^2 v^2}{3(1 - \nu^2)} L^{3/4}.
\]

Fitting the data for the distance dependence of the strain, shown in Extended Data Fig. 1d, to the expression \( \lambda = \lambda_0 + cL^{3/4} \), we obtain the constant \( c = 0.154 \pm 0.005 \), consistent with the above estimate. The value of the offset \( \lambda_0 = (6 \pm 0.3) \) nm suggests that this formula breaks down at short distances.

To understand why the ID scaling of the buckling period is consistent with our results, we consider the sketch shown in Extended Data Fig. 1b. We note that it is unlikely that both ridges collapse at the same instant. Now if we suppose that the ridge marked by the green line in the sketch collapses first, it will produce a set of roughly parallel wrinkles whose spacing increases with distance as the strain decreases according to the scaling formula above. When subsequently the yellow ridge collapses, it produces a similar set of wrinkles roughly parallel to itself. The points of intersection of the two wrinkle sets will thus produce a triangular pattern of crests (black dots) while the areas in between will be troughs.

Buckling transitions in thin stiff membranes have been studied extensively both experimentally and theoretically in the context of mechanical engineering. The details of the patterns that emerge after the buckling transition has taken place are controlled by boundary geometry and the strain distribution. Depending on the value of these parameters, a variety of buckling patterns are observed, including square, hexagonal, herringbone and stripes.

Flat areas in G/NbSe$_2$ and G/hBN samples
Superposing two 2D crystal structures produces a moiré pattern whose period is controlled by the two atomic lattice constants, \( a \) and \( b \), and by the angle between their crystal orientations. The largest moiré period, which is obtained when the two crystals are aligned, is given by \( \lambda_{\text{max}} = (1 + \delta/a) \), where \( \delta = (b - a)/a \) is the lattice mismatch.

The lattice constants for graphene and NbSe$_2$ are \( a = 0.246 \) nm and \( b = 0.36 \) nm, respectively, leading to \( \lambda_{\text{max}} = 0.77 \) nm. This is more than an order of magnitude smaller than the superlattice periods observed in our work, immediately ruling out an interpretation in terms of a moiré pattern.

To further confirm that the observed pattern is not due to a moiré structure, we show in Extended Data Fig. 2 the atomically resolved topography of a region far from the two ridges, which shows the honeycomb structure characteristic of flat graphene (Extended Data Fig. 2b). In this region, the featureless STM topography of a region far from the two ridges, which shows the honeycomb structure characteristic of flat graphene (Extended Data Fig. 2b).

Buckling patterns and dI/dV maps
The two panels of Extended Data Fig. 3a show the STM topography of the buckled graphene in the G/NbSe$_2$ sample taken with two different bias voltages. The blue lines are guides to the eye, connecting the crests. The crests remain bright for different bias voltages, consistent with their higher topography.

In Extended Data Fig. 3b, we show the dI/dV map at an energy corresponding to the \( N = 0 \) PLL in the crest area of the G/NbSe$_2$ sample.
The uniform LDOS represented by this map differs from the petal structure expected for a Gaussian bump and reflects the unique geometry of the PMF induced by the buckled structure, which further confirms the theoretical model.

Transition area in the G/NbSe₂ sample
Extended Data Fig. 4a shows the theoretical contour plot of the LDOS spectra connecting two crest areas (see also the upper panel of Fig. 3g). In the transition area labelled by the yellow dashed line, we note that features from the crest (green arrows) and trough (red arrows) coexist. This coexistence is also observed in the experimental dI/dV spectrum (Extended Data Fig. 4b), which exhibits peaks that can be traced back to both the crest (green arrows) and the trough (red arrows) regions.

PMF dependence on superlattice period
Extended Data Fig. 5 shows the simulated LDOS in the crest region as a function of PMF amplitude for several values of the superlattice period, as marked. The dashed lines represent the field dependence of the LL energy in uniform fields. We note that as the lattice spacing increases, the spectra start approaching the unstrained LL sequence at lower values of the PMF. This is consistent with the fact that LLs, which correspond to cyclotron motion, can only form if the magnetic field is large enough to satisfy the magnetic flux quantum condition. The choice of the gauge is arbitrary, but we may choose $A_0 = 0$. Hence, our vector potential is then given by $A_j = \int B(x,y) dy$, where $B(x,y)$, shown in Extended Data Fig. 8a, is given by equation (1). This leads to

\[ A_x = \frac{a}{2 \pi} \left( \frac{1}{b_y} \sin(b \cdot r) + \frac{1}{b_{2y}} \sin(b \cdot r) + \frac{1}{b_3} \sin(b \cdot r) \right) \]

Substituting $b_0 = t_0(1 + \delta_t)$ and expanding equation (4) up to first order, we obtain the following expression for the vector potential

\[ (A_x, A_y) = -\frac{1}{2\pi} \left[ 2\delta_t - \delta_t^2 - \delta_t \right] \]

where $\delta_t$, $\delta_2$ and $\delta_3$ are the strain modulations of hopping energies along the directions of graphene's nearest neighbours $\delta_1$, $\delta_2$, and $\delta_3$, as shown in Extended Data Fig. 8b, and $v_0 = 3/\Phi_0$ is the Fermi velocity. The choice of the gauge ($A_0 = 0$) results in $\delta_t = \delta_2 = \delta_3 = 0$. We choose $\delta_t = -\delta t$ and, finally, the strain modified hopping energies are given by

\[ t_1 = t_0 \left( 1 - \frac{3\delta_t a_{cc}}{2\Phi_0} \right) \]

\[ t_2 = t_0 \left( 1 + \frac{3\delta_t a_{cc}}{2\Phi_0} \right) \]

where $\Phi_0 = h/e$ is the magnetic flux quantum.

Theoretical results for the G/hBN sample
To simulate the buckling pattern in graphene on hBN, we use a similar expression as in the case of graphene on NbSe₂, given by equation (2), but without the last cosine term:

\[ B_{PMF}(x,y) = B [\cos(b_1 \cdot r) + \cos(b_2 \cdot r)] \]

with $b_1 = (2m/\alpha_0^2)(0,1)$ and $b_2 = (2m/\alpha_0^2)(1,0)$. This changes the symmetry of the unit cell from triangular to rectangular. The profile of the field is shown in Extended Data Fig. 9a with the unit cell marked by the dashed rectangle. The size of the unit cell is chosen so as to match the buckling periods shown in Fig. 5a. The LDOS in the crest region is given in Extended Data Fig. 9b, where clear LLs can be observed in the spectrum. A cut of the LDOS map at a constant value of $B = 62 \, T$ shows that LLs scale with the square root of the LL index (see Extended Data Figs. 9c, d) and result in an effective field of $B_{eff} = 100 \, T$. Moving towards the transition region, the LDOS spectrum shows the flattening of the bands with increasing field amplitude.

Flat-band structure in buckled G/NbSe₂
In Extended Data Fig. 7 we plot the band structure and LDOS in the trough region for $B = 140 \, T$ (Extended Data Fig. 7a, b) and $B = 180 \, T$ (Extended Data Fig. 7c, d). The figure shows the flattening of the bands with increasing field amplitude.

Tight-binding model for the strained triangular lattice
The effect of strain is included in the tight-binding Hamiltonian through the modulation of the hopping energy. This is given by

\[ t_{ij} = t_{0e} \exp(-\beta \delta_{ij} a_{cc}^{-1}) \]

where $\beta$ is the decay coefficient, $a_{cc}$ is the unstrained carbon–carbon bond, and $\delta_{ij}$ is the strained bond length defined by the strain tensor $\tau$ as

\[ d_{ij} = (1 + \varepsilon) \delta_{ij} \]

where $\delta_{ij}$ is the vector in the direction of the bond between atoms $i$ and $j$, and $\varepsilon$ is the unitary matrix. Changes in the hopping energies generate a strain-induced vector potential in the system, which in the case of hexagonal lattices is given by

\[ A_x = -\frac{1}{2\pi} \sum_j \delta t_{ij} e^{i(k_x - k_y)} \]

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\[ A_x = -\frac{1}{2\pi} \sum_j \delta t_{ij} e^{i(k_x - k_y)} \]

The corresponding PMF is calculated using

\[ B = \nabla \times A = \left[ \partial_x A_y - \partial_y A_x \right] z \]

Owing to gauge invariance, we may choose $A_0 = 0$. Hence, our vector potential is then given by $A_j = \int B(x,y) dy$, where $B(x,y)$, shown in Extended Data Fig. 8a, is given by equation (1). This leads to

\[ A_x = \frac{a}{2 \pi} \left( \frac{1}{b_y} \sin(b \cdot r) + \frac{1}{b_{2y}} \sin(b \cdot r) + \frac{1}{b_3} \sin(b \cdot r) \right) \]

Substituting $b_0 = t_0(1 + \delta_t)$ and expanding equation (4) up to first order, we obtain the following expression for the vector potential

\[ (A_x, A_y) = -\frac{1}{2\pi} \left[ 2\delta_t - \delta_t^2 - \delta_t \right] \]

where $\delta_t$, $\delta_2$ and $\delta_3$ are the strain modulations of hopping energies along the directions of graphene's nearest neighbours $\delta_1$, $\delta_2$, and $\delta_3$, as shown in Extended Data Fig. 8b, and $v_0 = 3\Phi_0$ is the Fermi velocity. The choice of the gauge ($A_0 = 0$) results in $\delta_t = \delta_2 = \delta_3 = 0$. We choose $\delta_t = -\delta t$ and, finally, the strain modified hopping energies are given by

\[ t_1 = t_0 \left( 1 - \frac{3\delta_t a_{cc}}{2\Phi_0} \right) \]

\[ t_2 = t_0 \left( 1 + \frac{3\delta_t a_{cc}}{2\Phi_0} \right) \]

where $\Phi_0 = h/e$ is the magnetic flux quantum.
changes substantially, as shown by Extended Data Fig. 9c. Here, the spectrum does not show LLs, which is expected since there is no PMF. However, the LDOS reveals new sets of peaks that depend weakly on the amplitude of the field. This is further confirmed in Extended Data Fig. 9d, which shows that the dispersion of these peaks with unit cell size $a$ is consistent with that expected of confinement states. Taking a cut of the LDOS map from Extended Data Fig. 9c at $B = 62$ T results in equidistant peaks separated by about $83$ meV as shown in Extended Data Fig. 9f, h.

**Robustness of the PLLs against disorder**

As seen in Fig. 1c, the rectangular buckling array in the G/hBN sample is not perfectly periodic as implied by the double cosine potential used in the simulation. It is then natural to ask how robust are the simulated DOS and the corresponding $dV/dI$ spectrum against lattice distortions. To address this question, we carried out numerical simulations where the periodicity condition was relaxed. As detailed below, we find that the PMF spectrum of the rectangular buckling structure is quite robust, and can survive substantial deviations from the perfectly periodic lattice structure.

To study the effect of relaxing the condition of perfect periodicity, we introduced a random variation in the unit cell of the PMF within a predefined range. The procedure is as follows. Since the original unit cell is too large, we reduced the larger unit vector to the size of the smaller one, that is, $a_x = a_x = 20$ nm. The PMF profile for this case is shown in Extended Data Fig. 10a. Changing the size of the unit cell should not change the physics of the problem, but numerically this substantially speeds up our calculations. The system is a circle of radius of 200 nm with absorbing boundary conditions applied at the edges (the method is described in detail in ref. 39). A vector potential is added to the Hamiltonian as described above, with the unit cell period given by $(1 + \Delta R_x) a_x, (1 + \Delta R_y) a_y$, where $R_x$ and $R_y$ are random numbers from a uniform distribution in the range $[-1, 1]$ and $\Delta$ is the weight parameter.

As an example, in Extended Data Fig. 10b–d we plot a few PMF profiles using $\Delta = 0.15, 0.25, 0.33$, respectively. The calculated DOS is shown in Extended Data Fig. 10e (the DOS is calculated using the kernel polynomial method, as explained in ref. 40). The blue curve in this plot shows the DOS of the perfectly periodic system. The peaks observed here are the flat bands, and the separation between the peaks is around 60 meV. As $\Delta$ is increased, the peaks are averaged out and eventually disappear for large $\Delta$, which is the expected result. However, up to $\Delta = 0.25$, the peaks are still present in spite of the substantial disorder introduced in the system.

In addition to the robustness of the PLL spectrum against lattice disorder, the resemblance between the spectral features of the G/hBN and G/NbSe$_2$ samples in the crest regions further indicates their common origin, as detailed below.

1. In both systems, the features are observed only in the buckled regions of the graphene membrane and are absent in the unbuckled parts of the sample.

2. In both systems, the buckling gives rise to a strain-induced PMF resulting in the PLL observed in the $dV/dI$ spectra. The PLL sequence, which is characterized by a peak at the Dirac point and a square-root dependence on level index, is observed on the crests, consistent with the numerical simulation results.

3. In both systems, the spectra in the regions between maxima of the PMF show confinement character, rather than PLLs. Specifically, they do not feature the peak at the Dirac point corresponding to the $N=0$ PLL and the peak sequence does not follow a square-root level index dependence. Instead the spectrum in this regime is consistent with magnetic confinement states.

**Transition region in the G/hBN sample**

In the case of the G/NbSe$_2$ sample, the crest and trough regions of the triangular buckling pattern observed in topography coincide with the maximum and minimum PMF, respectively. This designation is not as straightforward in the rectangular buckling pattern observed in the G/hBN sample. While in this sample the crest regions where the PMF has its maximum magnitude are readily identified in the topography as the intersection point between two of the quasi-1D wrinkles that form the rectangular buckling pattern (Fig. 1c), it is less easy to identify the transition regions where the PMF is vanishingly small. We instead used the fact that in the transition region the PMF vanishes, resulting in the disappearance of the PLLs and the characteristic peak at the CNP. By using this criterion, we identified the transition region marked by the circle in Fig. 5a.

**Data availability**

The data that support the findings of this study are available from the corresponding authors on reasonable request.

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**Author contributions**

J.M. and Y.J. performed STM/STS measurements. Y.J., J.M. and E.Y.A. designed the research strategy, performed data analysis and wrote the manuscript with input from all authors. S.P.M., M.A., L.C. and F.M.P. performed theoretical calculations. Y.C., A.K.G. and X.L. fabricated the devices. K.W. and T.T. provided hBN. E.Y.A. supervised the project.

**Competing interests**

The authors declare no competing interests.

**Additional information**

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Extended Data Fig. 1 | Buckling pattern of graphene. a, Large-area STM topography of G/NbSe₂ shows two ridges that delimit the buckling pattern (V_b = −0.3 V, I = 20 pA). b, Schematic of wrinkles arising from the compressive strain at each boundary ridge. Crests form at the wrinkle intersections, marked by black dots. c, Zoomed-in topography image of the triangular buckling pattern (V_b = 0.5 V, I = 20 pA) in a. d, The superlattice constant, measured along the line marked by the blue arrow in c, increases monotonically with distance from the apex where the two ridges meet. e, Height profile along the green arrow in a. f, Strain produced by the collapse of the ridges calculated from e, as described in Methods section ‘Buckling pattern formation’.
Extended Data Fig. 2 | Topography of unbuckled regions in the G/NbSe₂ sample. a, Main panel, STM topography of a flat (unbuckled) region of the G/NbSe₂ surface far from the ridges. Inset, dI/dV spectrum from the region shown in the main panel (V_b = 0.5 V, I = 30 pA). b, Atomic-resolution view of G/NbSe₂, in a (V_b = −0.3 V, I = 30 pA). c, Same as a but from a flat region of the G/hBN sample. Inset, dI/dV spectra of flat G/hBN for conditions of electron-doping (green trace) and hole-doping (red trace); V_b = −0.3 V, I = 20 pA.
Extended Data Fig. 3 | Topography of buckled regions in the G/NbSe₂ sample. a, STM topography of a region in the buckled graphene membrane measured with different bias voltages: 500 mV (left) and 50 mV (right).

b, dI/dV map over an area of size 6 nm × 6 nm in the crest region at the energy of the N = 0 PLL.
Extended Data Fig. 4 | Transition area in the triangular buckling pattern of the G/NbSe₃ sample. a, Theoretical contour plot of the LDOS spectra connecting two crest areas (at x = 0 nm and x = 25 nm; see Fig. 3g, upper panel) versus energy, E, and position, x. The colour scale bar represents the LDOS intensity. The yellow dashed line labels the LDOS spectrum in the transition region plotted in b. b, Experimental dI/dV spectrum in the transition region between crests and troughs. Green and red arrows indicate the corresponding peaks in a.
Extended Data Fig. 5 | Evolution of the calculated LDOS with PMF amplitude for several superlattice periods. Shown are contour plots of the LDOS for several values of \(a_{b}\) (left to right: 12 nm, 14 nm, 16 nm) in the crest region versus the amplitude of the magnetic field, \(B\), and energy, \(E\). Dashed lines represent the field dependence of the PLL energy in a uniform magnetic field given by the \(x\)-axis values.
**Extended Data Fig. 6** | Calculated PMF in the crest areas of the buckled G/NbSe₂ sample.  

**a,** LDOS cuts in the crest region from Fig. 3a, upper panel (A sublattice), for several values of $B$ and corresponding $B_{\text{eff}}$ (first and second columns in the key). The ratio of the effective PMF obtained from the PLL spectrum on the crests to the maximum PMF value ($B_{\text{eff}}/B_{\text{PMF}}^\text{max}$) is shown in the rightmost column of the key.  

**b,** Comparison of crest LDOS at $B_{\text{eff}} = 112$ T for two lattice constants (14.0 nm and 14.8 nm) in the regime where the $N=0$ peaks merge into one.
Extended Data Fig. 7 | Calculated low-energy band structure and LDOS in the trough regions of the buckled G/NbSe₂ sample. a, b, Band structure (a) and LDOS (b) for a PMF of 140 T. c, d, As a but for a PMF of 180 T. Calculations are for a superlattice period of 14 nm.
Extended Data Fig. 8 | Tight-binding model for a strained lattice. 

a. Calculated profile of the PMF given by equation (I) for lattice spacing $a_b = 14$ nm.

b. Schematic of nearest neighbour vectors, $\delta_1$, $\delta_2$, and $\delta_3$, in a graphene lattice.
Extended Data Fig. 9 | PMF for a rectangular buckling pattern in graphene.

a, Profile of the PMF in a rectangular buckling pattern. Dashed rectangle shows the magnetic unit cell. b, LDOS (sublattice averaged) versus the PMF amplitude $B$ and energy $E$ at a crest position in a (centre of red region marked by a green dot). The colour scale bar represents the LDOS intensity in arbitrary units. Note that the same result is obtained in the centre of troughs (blue regions) where the PMF sign is reversed. c, As b but for a point with zero field, marked in a by the magenta square. d, Contour plot of the LDOS versus energy and superlattice spacing shows the evolution of the confinement levels with unit cell size. The colour scale bar represents the LDOS intensity. e, Cut of the LDOS from b for a constant value of the field, $B = 62$ T, shown by the dashed white line. f, Cut of the LDOS from c for a constant value of the field, $B = 62$ T, shown by the dashed white line. g, Fitting the peak sequence to a square-root dependence on the PLL index gives an effective PMF of 100 T. h, The peak sequence in f gives a linear dependence on the peak index with an energy spacing of about 83 meV.
Extended Data Fig. 10 | DOS versus unit cell size in the presence of lattice disorder. a–d, The PMF profile used for calculating the DOS shown in e. The unit cell period variation range is given by (1 ± Δ), with \( a_0 = 20 \) nm and \( Δ = 0 \) (a), 0.15 (b), 0.25 (c) and 0.33 (d). e, DOS obtained for different values of Δ given in the key for \( B = 62 \) T (as in Extended Data Fig. 9).