Competing Charge Density Waves Probed by Nonlinear Transport and Noise in the Second and Third Landau Levels

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Charge density waves (CDWs) in the second and third Landau levels (LLs) are investigated by both nonlinear electronic transport and noise. The use of a Corbino geometry ensures that only bulk properties are probed, with no contribution from edge states. Sliding transport of CDWs is revealed by narrow band noise in reentrant quantum Hall states $R2a$ and $R2c$ of the second LL, as well as in pinned CDWs of the third LL. Competition between various phases—stripe, pinned CDW, or fractional quantum Hall liquid—in both LLs are clearly revealed by combining noise data with maps of conductivity versus magnetic field and bias voltage.

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Spontaneous charge ordering is one of the many intriguing quantum phenomena occurring in a 2D electron gas (2DEG) under a magnetic field. In the first ($N = 0$) Landau level (LL), the short-range attractive part of Coulomb interaction is known to be responsible for the condensation of quasiparticles into an incompressible Laughlin liquid [1] hosting a fractional quantum Hall effect (FQHE) and carrying fractional charges. In higher LLs ($N \geq 2$), however, the situation is markedly different, as the combination of short-range attractive with long-range repulsive Coulomb interaction leads to electronic phases forming charge density waves (CDWs). At half filling factor of these LLs, $\nu^* = \nu - [\nu] = 1/2$, with $[\nu]$ defined as the integer part of $\nu = n_s h/eB$ (where n_s is the electron density and B is the magnetic field), an alternation between stripes of filling $\nu^* = 1$ and $\nu^* = 0$ with a spatial period on the order of the cyclotron length leads to a ground state with broken symmetry, believed to be a smectic liquid crystal. At finite temperature, a Berezinskii-Kosterlitz-Thouless (BKT) transition is predicted [2,3] between a smectic and a nematic phase, followed by a melting at higher energy, restoring the isotropic phase. Several observations of anisotropic transport supporting these theories have been reported [4–7]. At lower partial filling factor $\nu^* \approx M/(3N)$, Hartree-Fock calculations [8,9] also predict a pinned bubble crystal with M electrons (or holes) per bubble, which was observed with microwave conductivity measurements [10]. In between such phases, at $\nu = 1/4$ and $\nu = 3/4$, pinned CDW phases have been observed [11] and, albeit still debated, could be composed of stripe segments with a depinning transition to a nematic electron liquid crystal at finite bias voltage [6].

In the second ($N = 1$) Landau level (SLL), CDW and FQHE are known to compete, and a reentrant quantum Hall effect (RIQHE) is often observed among various FQHE states when the electron mobility is sufficiently high [12]. The RIQHE is characterized by a plateau in the Hall resistance at given noninteger values of partial filling factor ν^*. Although there are experimental evidences that RIQHE states are CDWs, their nature is still being highly debated [13–15]. At first sight, the absence of transport anisotropy suggested charge ordering in the form of bubble phases; however, recent experiments involving resistively detected nuclear magnetic resonances (RDNMRs) [14] show that RIQHE phases near $\nu^* = 1/2$ ($R2b$ and $R2c$) host polarized and unpolarized spin regions, suggestive of a stripe phase. In contrast, another RDNMR experiment [13], focusing on RIQHE phases at $\nu^* < 1/3$ ($R2a$ and $R2d$), suggests that these are more likely bubble phases. Furthermore, other recent works show that, in spite of a competition, CDW and FQHE phases could even coexist at a same ν^* [16,17].

Most previous transport investigations of CDW phases have been performed in van der Pauw (VdP) or Hall bar geometries, where both bulk and edge transport contribute. With the exception of Refs. [18–21], and to our knowledge, only the resistivity and *not* the conductivity has been mapped out as function of dc bias in the SLL [15] and in the third Landau level (TLL) [6]. This is precisely the purpose of this Letter where bulk electronic transport properties in both the SLL and TLL are investigated in ultrahigh mobility Corbino-shaped 2DEG samples. The differential conductance $G = \partial I/\partial V$, as well as the current noise spectral density S_{II}, was measured as a function of dc bias voltage V_{dc} and magnetic field in samples with different ring sizes. This allowed us to draw several conclusions: (i) transport involves sliding CDWs, suggesting a stripelike order CDW such as a nematic electron liquid crystal in the RIQHE of the SLL and away from half filling in the TLL; (ii) a bubble-phase scenario for three RIQHE states in the SLL is unlikely; and (iii) FQHE and CDWs can coexist in the SLL.

Three samples in concentric Corbino geometries have been fabricated on the same 2DEG with electron density $n_s = 3.8 \times 10^{11}$ cm^{-2}. Contact inner and outer diameters $D_{\mathrm{in}}/D_{\mathrm{out}}$ are 150/750, 960/1000, and 1300/1400 μm, respectively, for $C1$, $C2$, and $C3$ [see inset of Fig. 1(a)]. Details pertaining to the wafer design, fabrication, cooldown procedure, mobility, and noise measurements are provided in the Supplemental Material [22]. Except when noted, measurements have been performed at base temperature (7 mK) with an estimated electron temperature of 20 mK. The zero-bias conductivity σ_{xx} versus magnetic field is shown in Fig. 1(a) for sample $C1$. The transition between Shubnikov–de Haas oscillations and integer quantum Hall regime occurs at $B \sim 1$ T. There, the conductivity σ_{xx} maxima are very close to 0.5 e^2/h, as expected [23,24], and vary by less than ~10% for temperature between 20 and 200 mK in both spin-resolved branches. At higher magnetic fields in Landau levels $N < 5$, σ_{xx} departs from 0.5 e^2/h. As shown in Fig. 1(c), the conductivity maxima vary non-monotonically with temperature and increase from 20 to 50 mK, reaching ~$1.7e^2/h$ at $\nu = 9/2$, and then decrease with increasing temperature. Finally, we note that the temperature dependence of the spin-down phases $\nu = 9/2$ and $\nu = 13/2$ are more robust than for the spin-up $\nu = 11/2$ and $\nu = 15/2$, as has been observed in the stripe phase in the VdP geometry [4,5].

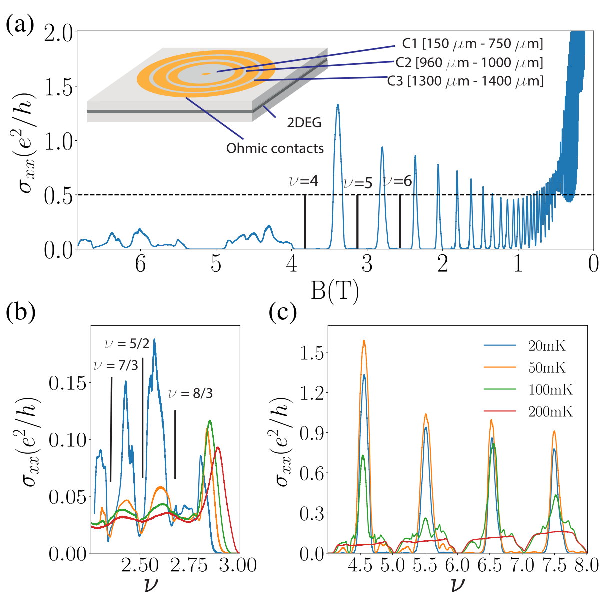

FIG. 1. (a) Conductivity σ_{xx} versus magnetic field B for sample $C1$. (Inset) Schematics of the samples. (b),(c) σ_{xx} of sample $C1$ at 20 mK (blue curve), 50 mK (orange curve), 100 mK (green curve), and 200 mK (red curve) in the SLL lower spin branch (b) and in the $N = 2$ and $N = 3$ LL (c).

Our measurements in the TLL are reported in Fig. 2. Panel (a) of this figure shows a color intensity plot of σ_{xx} versus dc bias voltage V_{dc} and filling factor ν in the lower spin branch of the TLL ($4 < \nu < 5$) for sample $C1$. The nonlinear transport measurements reveal important features that are absent at $V_{\mathrm{dc}} = 0$. We first focus on the central region corresponding to the stripe phase around $\nu = 9/2$. Corbino samples have rotational invariance; however, the anisotropy of the stripe phase appears as follows. The conductivity in the Corbino geometry is given by $\sigma_{xx} = (G/2\pi)\ln(D_{\mathrm{out}}/D_{\mathrm{in}})$, where G is the differential conductance and D_{in} (D_{out}) is the inner (outer) ring diameter. In an isotropic phase, σ_{xx} should not depend on the sample size. Yet, we observe that, in the (presumably anisotropic) stripe phase, the conductivity ratios of the three different samples are far from the expected value

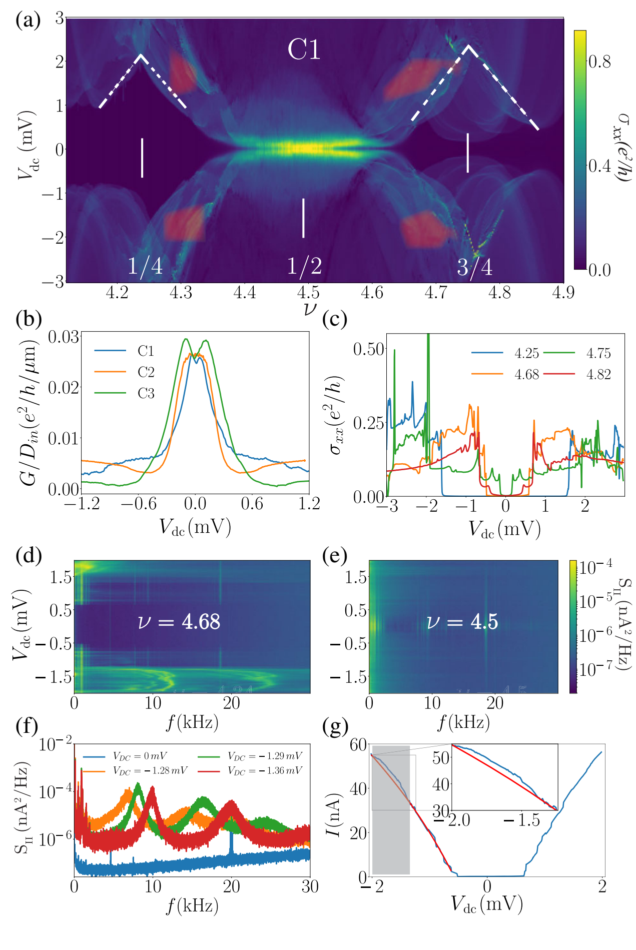

FIG. 2. (a) σ_{xx} in the TLL versus V_{dc} and ν in $C1$. Narrow band noise was observed in red overlay regions. (b) G/D_{in} (G being the conductance and D_{in} the inner contact diameter) versus V_{dc} at $\nu = 9/2$ in the three samples. (c) σ_{xx} versus V_{dc} at $\nu = 4.25$, 4.68, 4.75, 4.82 in $C1$. (d),(e) Noise spectral density $S_{II}(f)$ versus frequency f at $\nu = 4.68$ and 4.5. (f) $S_{II}(f)$ versus frequency f at $\nu = 4.68$ for $V_{\mathrm{dc}} = 0$, -1.28, -1.29, -1.36 mV. (g) (Blue) dc current I versus V_{dc} at $\nu = 4.68$ with a zoom on narrow band noise region in central inset. (Red) Cubic interpolation of $I(V_{\mathrm{dc}})$. The grayed zone is where narrow band noise occurs.

of one: at 20 mK and $V_{\mathrm{dc}} = 0\ V$, $\sigma_{xx}^{C1}/\sigma_{xx}^{C2} = 2.6$ and $\sigma_{xx}^{C1}/\sigma_{xx}^{C3} = 6.8$. This phase is known to have a preferred direction (the so-called easy axis), and as a consequence, we rather expect the conductance to be proportional to the number of stripes linking the two contacts, i.e., in our case to D_{in}. This is what is observed here: as shown in Fig. 2(b), the ratio of conductance G at $V_{\mathrm{dc}} = 0\ V$ over D_{in} is $G/D_{\mathrm{in}} = 0.026\ e^2/h\,\mu\mathrm{m}^{-1}$, as extracted from a linear fit of G versus D_{in} (see [22]). In contrast, at 200 mK, where the stripe phase is expected to have melted, the conductivity ratios are found to be $\sigma_{xx}^{C1}/\sigma_{xx}^{C2} \approx 0.7$ and much closer to the expected value of one. Finally, we observe three regimes of conductance for samples $C1$ and $C3$ [see Fig. 2(b)] with increasing bias voltage: one that increases with V_{dc}, a second where it decreases, and a third that is nearly constant. This is consistent with a smooth BKT transition between a smectic to a nematic phase and then to an isotropic phase, as observed recently in Ref. [25].

At filling factors deviating from $\nu = 9/2$, the differential conductance is observed to vary abruptly at nonzero dc bias forming diamond-shaped regions; see dashed lines in Fig. 2(a). In addition, a pronounced hysteresis upon voltage sweep direction is also observed. This is consistent with the depinning transition typical of a pinned CDW [11,18]. The diamonds are located at filling factors in the vicinity of $\nu^* = 1/4$ and $\nu^* = 3/4$, as was previously reported [6,11,18]. We note the situation is, however, more complex for $\nu^* = 3/4$, where σ_{xx} has several jumps, which could be different depinning transitions occurring at different threshold bias voltages, as exemplified by the green curve of Fig. 2(c). Finally, a finite bias voltage may introduce LL tilting, which could then lead to current flow in higher LLs by way of mechanisms such as breakdown. However this is unlikely here since the typical threshold values $V_{\mathrm{dc}} \simeq 2$ mV are well below the LLs spacing ($\Delta \simeq 6$ meV at $B = 3.5$ T), and the typical breakdown voltage values measured at $\nu = 3$ are on the order of $V_{\mathrm{dc}} \simeq 10$ mV.

The current noise spectral density $S_{II}(f)$ as a function of dc bias voltage V_{dc} was measured in a dc to 65 kHz bandwidth. Examples of such spectra are presented in Fig. 2(f) for fixed dc bias voltage. The voltage dependence of the spectra are shown as color intensity plots in Figs. 2(d) and 2(e) for sample $C1$ at two different filling factors in the TLL. In certain ranges of dc bias voltage, the noise spectra show peaks at finite frequencies, often followed by several harmonics, as shown for $\nu = 4.68$ in Fig. 2(f). This narrow band noise (NBN) occurs at the boundary separating stripes and pinned CDWs around $\nu^* \approx 0.3$ and $\nu^* \approx 0.7$ and often at bias voltage significantly above depinning threshold voltage [see regions in red overlay in Fig. 2(a)]. NBN was reported before in [26] for $\nu = 4 + 1/4$ and $6 + 1/4$; however, there was no clear understanding of these phenomena. The NBN observed here is reminiscent of "washboard noise" associated with sliding mode conductivity of CDWs [27]. In this scenario, the current carried by a sliding CDW is given by $I_{\mathrm{CDW}} = ef_0\lambda n_c$, where $f_0 = v_d/\lambda$ is the fundamental frequency (here on the order of 10 kHz), λ is the periodicity of the CDW, v_d is the drift velocity, and n_c is the density of electrons condensed in the sliding CDW. As there is already current flowing in the sample when NBN occurs, it is difficult to measure precisely I_{CDW} as a function of bias voltage. However, by interpolating the dc current versus bias voltage $I(V_{\mathrm{dc}})$ [blue curve in Fig. 2(g)] with a cubic polynomial [red curve in Fig. 2(g)] and subtracting it from $I(V_{\mathrm{dc}})$ (see [22]), a current increase is observed. The voltage range in which an increase of the dc current is observed coincides with that where NBN is observed [shaded region in Fig. 2(g)]. At $\nu = 4.68$, we find $I_{\mathrm{CDW}}/f_0 = 2.46 \times 10^{-13}$ A s. Assuming further a CDW periodicity on the order of the cyclotron radius [8] $l_c = \sqrt{N+1}\,l_B \sim 31.8$ nm (l_B being the magnetic length), an estimate for the electron density in the CDW is found to be $n_c \sim 4.8 \times 10^9\ \mathrm{cm}^{-2}$. The velocity of the sliding CDW can also be estimated, $v_d \sim 380\ \mu\mathrm{m\,s}^{-1}$. Given the electron density $n_s = 3.8 \times 10^{11}\ \mathrm{cm}^{-2}$, at $\nu = 4.68$, the density of charge in the 68% filled lower spin branch TLL is $n_L = 5.1 \times 10^{10}\ \mathrm{cm}^{-2}$ and, as a consequence, the sliding CDW would carry 9% of the charges present in this LL. The observation of narrow band noise at biases above the depinning voltage, and given that sliding CDWs are generally observed with depinning of 1D electron crystals along the crystal wave vector direction suggests here the occurrence of two depinning transitions. First, a depinning transition occurring in the easy direction (perpendicular to the crystal wave vector) allowing for the current to flow, then a sliding of the crystal, likely in the crystal wave vector direction. We conclude that an electron nematic liquid crystal that is susceptible to being pinned in both directions is a good candidate to support our observations and is consistent with the previous work of Ref. [6].

Similar measurements have been carried out in the SLL and reported in Fig. 3. The Corbino geometry does not provide any information regarding the Hall resistance, and as such, it is difficult to unambiguously identify the RIQHE. However, the position of the conductance maxima, as well as their temperature dependence [see, for example, Fig. 1(b) for $C1$], can be compared and identified with previously RIQHE states and identified as $R2a$, $R2b$, and $R2c$, per the nomenclature of Refs. [12,28,29]. Focusing on $R2c$ in $C1$ [Fig. 3(a)], we observe that it holds peculiar similarities with the stripe phases observed in the TLL. First, the maximum conductivity $\sigma_{xx}^{\max}$ is singularly enhanced at low temperatures and reaches $\sigma_{xx}^{\max -20\ \mathrm{mK}} = 0.3e^2/h$ with $\sigma_{xx}^{\max -20\ \mathrm{mK}}/\sigma_{xx}^{\max -200\ \mathrm{mK}} > 10$ [Fig. 1(b)]. Comparing it to the CDWs in the TLL, such an increase is observed only in the stripe phase, where at $\nu = 9/2$, $\sigma_{xx}^{\max -20\ \mathrm{mK}}/\sigma_{xx}^{\max -200\ \mathrm{mK}} \simeq 20$. This behavior is not observed in the bubble phases. These peaks in conductance are present in $R2a$, $R2b$, and $R2c$ in all our Corbino samples and, while they resemble the stripe conductivity

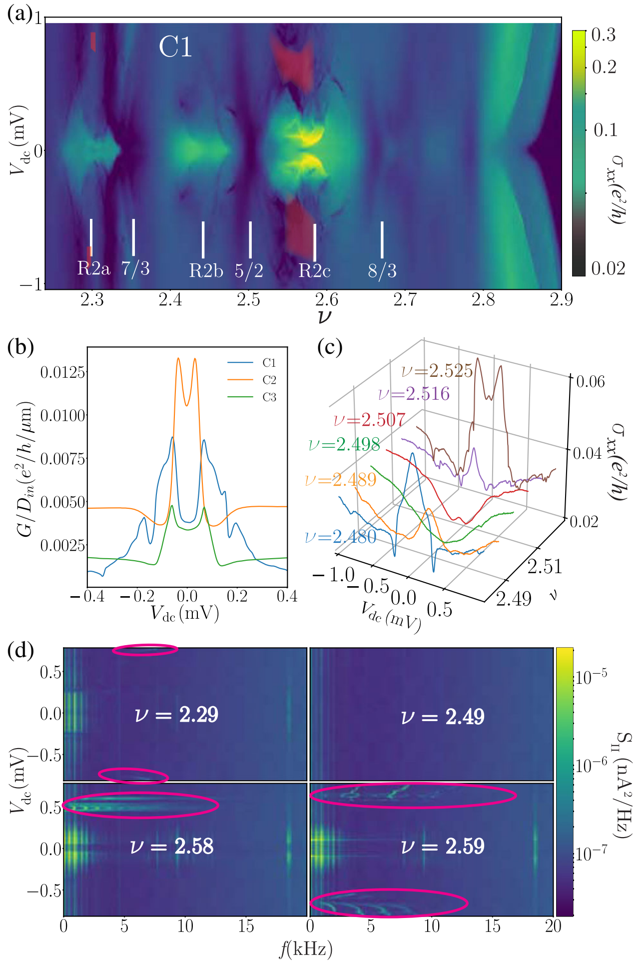

FIG. 3. (a) σ_{xx} in the SLL versus $V_{\rm dc}$ and ν in $C1$. Narrow band noise was observed in red overlay regions. (b) $G/D_{\rm in}$ versus $V_{\rm dc}$ in $R2c$ center ($\nu = 2.58$) for the three samples. (c) σ_{xx} versus $V_{\rm dc}$ at different filling factors around $\nu = 5/2$ in $C1$. (d) Current noise spectral density $S_{II}(f)$ versus frequency f at $\nu = 2.29$, 2.49, 2.58, 2.59.

maxima observed at $\nu = 9/2$, they disappear (or melt) at lower Joule power P dissipated in the sample. For example, $P \simeq 3$ pW was sufficient to destroy the conductance peak in $R2c$, whereas a $P \simeq 18$ pW is required to destroy the stripe phase in $C1$ at $\nu = 9/2$. We take this as evidence disfavoring scenarios based on isotropic bubble phases because it is difficult to reconcile it with the conductance enhancement at low temperatures for these RIQHE states. However, these phases cannot be associated with the stripe phase occurring at $\nu = 9/2$ because here the conductance is not proportional to the ring diameter $D_{\rm in}$ [Fig. 3(b)].

Our σ_{xx} data also suggest a coexistence occurring between CDWs and FQHE states in the SLL, as was previously reported in [17] with optical measurement. To illustrate it, we focus on the $\nu = 5/2$ FQHE state and its vicinity [Fig. 3(c)]. At $\nu = 5/2$, the conductivity minima is at zero-bias voltage, as expected for a FQHE state [green curve in Fig. 3(c)]. As soon as we depart from the exact filling factor $\nu = 5/2$, a maximum in the conductivity is observed at zero-bias voltage, followed by a local minimum at finite bias [red and orange curves in Fig. 3(c)]. Already at $\nu = 2.52$ [brown curve in Fig. 3(c)] the conductivity resembles that of the RIQHE phase; i.e., it decreases with increasing bias voltage as crystalline order melts, as in Fig. 3(b). Previous work suggested the onset melting energy for RIQHE states to be lower than the FQHE gap [29,30], and since σ_{xx} give a direct access to bulk conductivity without any contribution from edge states (unlike in [31–33]), the zero-bias peak in the conductivity points toward phase coexistence. First, the crystal melts with increasing bias voltage, whereas the FQHE state vanishes at higher bias voltage. A similar situation where a competition occurs between a series of FQHE states and the Wigner crystal, albeit with increasing temperature rather than dc bias, has been previously reported deep in the first Landau level [34]. We also observe a similar coexistence between electron liquids and CDWs at filling factors in the vicinity of $\nu = 7/3$ and $\nu = 8/3$ FQHE states, although in a less pronounced way.

NBN was also observed in the SLL for $R2c$ and to a lesser extent in $R2a$, as shown in Fig. 3(d). This is, to our knowledge, the first observation of NBN in the SLL. Here, the typical fundamental frequency observed is 5–10 times lower than in the TLL. Applying a similar interpolation technique, we find in $R2c$ (at $\nu = 2.58$) that $I_{\rm CDW}/f_0 \approx 8.43 \times 10^{-14}$ A s [22]. Given that here the cyclotron length is $l_c = 23.4$ nm, we estimate the charge density in the sliding CDW to be $n_c \simeq 2.2 \times 10^9$ cm^{-2} with a drift velocity of $v_d = 23.4$ μm $\cdot$ s^{-1}. At $\nu = 2.58$, given the electron density in the last LL being $n_L = 5.52 \times 10^{10}$ cm^{-2}, the sliding CDW corresponds to 4% of the SLL lower spin branch electron density. This is consistent with what we have observed in the TLL and provides confidence that a sliding CDW is a reasonable explanation. Finally, as in the TLL, the sliding CDW points toward a depinning transition of an electron liquid crystal, implying here that such a phase is present in reentrant states $R2a$ and $R2c$.

To conclude, narrow band noise observations show that CDWs in the TLL and RIQHE states $R2a$ and $R2c$ in the SLL very likely contain a stripelike order susceptible of being pinned, such as for a nematic electron liquid crystal. The combination of these observations with conductivity maps versus dc bias taken in the SLL and TLL show that RIQHE states $R2a$, $R2b$, and $R2c$ are unlikely to be bubble states, and instead points toward an electron liquid crystal ordering that can coexist with FQHE liquids.

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