Observation of a transition from a topologically ordered to a spontaneously broken symmetry phase

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Until the late 1980s, phases of matter were understood in terms of Landau’s symmetry-breaking theory. Following the discovery of the quantum Hall effect, the introduction of a second class of phases, those with topological order, was necessary. Phase transitions within the first class of phases involve a change in symmetry, whereas those between topological phases require a change in topological order. However, in rare cases, transitions may occur between the two classes, in which the vanishing of the topological order is accompanied by the emergence of a broken symmetry. Here, we report the existence of such a transition in a two-dimensional electron gas hosted by a GaAs/AlGaAs crystal. When tuned by hydrostatic pressure, the $v = 5/2$ fractional quantum Hall state, believed to be a prototypical non-Abelian topological phase, gives way to a quantum Hall nematic phase. Remarkably, this nematic phase develops spontaneously, in the absence of any externally applied symmetry-breaking fields.

Numerous condensed matter systems exhibit phases with broken rotational symmetry, often referred to as electronic nematic phases\textsuperscript{4-7}. These phases may have additional broken symmetries\textsuperscript{8}. The intertwining of nematic order and other orders has recently elicited heightened interest. For example, nematic order and superconducting order accompany each other in high-$T_c$ superconductors\textsuperscript{8-10} and may coexist in confined $p$-wave superfluids\textsuperscript{11}.

The traditional phases of matter, such as the nematic phase or superconductors, are distinguished by their order parameters\textsuperscript{12}. However, certain phases cannot be described by a local order parameter. These phases, referred to as topological phases, are instead classified according to their topological order as measured by topological invariants\textsuperscript{13}. Topological phases often have a degenerate ground state, a gap in their excitation spectrum, and possess current-carrying edge states. The integer\textsuperscript{14} and fractional quantum Hall states (FQHS; ref. 15) forming in the two-dimensional electron gas (2DEG) are prototypical topological phases.

A phase transition from a topological phase to a nematic phase is expected to violate Landau’s rules and may be of a novel kind, as both the symmetry and the topological order need to change across such a transition. The FQHS at $v = 5/2$, believed to be a special topological phase with non-Abelian properties\textsuperscript{16-18}, is expected to have an instability towards a nematic phase\textsuperscript{19-21}. In transport, the broken rotational symmetry of a nematic phase is manifest in an anisotropic resistance. A transition at $v = 5/2$ from the isotropic FQHS to an anisotropic state has so far only been observed in the presence of a symmetry-breaking in-plane magnetic field\textsuperscript{22-28}. However, an externally applied symmetry-breaking field is always expected to favour the associated broken symmetry phase. An intriguing question is, therefore, whether or not a transition from a topological phase to a broken symmetry phase may occur spontaneously—that is, in the absence of any symmetry-breaking fields.

We investigate possible instabilities of the FQHS at $v = 5/2$ by magnetoresistance measurements under hydrostatic pressure $P$. When a 2DEG of density $n$ is exposed to a perpendicularly applied magnetic field $B_z$, a number $v = nh/eB_z$ of equidistant Landau levels will be filled\textsuperscript{29}. We focus on the region called the second Landau level, specifically the range of Landau level filling factors $2 < v < 3$. The filling factor of interest $v = 5/2$ is located in the middle of this range. In Fig. 1 we show the longitudinal resistance measured at three different pressures at a temperature $T \simeq 12$ mK. The longitudinal resistance is monitored along two mutually perpendicular crystallographic directions of the GaAs: $R_{XX}$ is obtained from the current bias $I$ applied and the voltage drop measured along the [110] crystal direction, whereas $R_{YY}$ is measured along the [110] direction. Details of our sample and the pressure cell used can be found in Methods.

In Fig. 1a we show the magnetoresistances at $P = 6.95$ kbar. The longitudinal resistances $R_{XX}$ and $R_{YY}$ exhibit sharp minima at $v = 5/2$. As shown in the Supplementary Information, these resistance minima are accompanied by a plateau at $2h/5e^2$ in the Hall resistance, indicating therefore a fractional quantum Hall ground state at $v = 5/2$ (refs 17, 18). We note that $R_{XX}$ and $R_{YY}$ measured in the vicinity of $v = 5/2$ along the different sample edges are nearly equal. We thus find that, similarly to measurements performed on samples in the ambient\textsuperscript{19}, the longitudinal resistance near $v = 5/2$ measured at $P = 6.95$ kbar is isotropic, and therefore the ground state is a rotationally invariant FQHS. As the pressure is increased to $P = 7.60$ kbar, the longitudinal resistance near $v = 5/2$ remains isotropic. However, as seen in Fig. 1b, the strong minima in $R_{XX}$ and $R_{YY}$ are no longer present.

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Figure 1 | Dependence of the magnetoresistance on hydrostatic pressure $P$ in the second Landau level. The green traces show $R_{XX}$ and the red traces show $R_{YY}$, as measured along two mutually perpendicular crystallographic directions of GaAs. Diagrams in the right indicate the circuit configurations used to obtain $R_{XX}$ and $R_{YY}$. As the pressure is increased, at $v = 5/2$ we observe the following sequence of ground states: an isotropic FQHS (a), a nearly isotropic Fermi liquid (b), and the nematic phase (c). The data is taken at $T = 12$ mK.

at this pressure. The finite and isotropic resistance at $v = 5/2$, exhibiting a weak dependence on the filling factor, is indicative of proximity of the ground state to a compressible isotropic Fermi liquid. Our data at $v = 5/2$, shown in Fig. 1b, suggest therefore that the fractional quantum Hall ground state at $v = 5/2$ approaches an instability. A further increase in pressure to $P = 8.26$ kbar causes a strong minimum to reappear in $R_{YY}$ at $v = 5/2$. As seen in Fig. 1c, this minimum in $R_{YY}$ is visibly wider—in that it spans a larger range of filling factors—than that at $P = 6.95$ kbar. The most marked change, however, is in $R_{XX}$, which, in contrast to lower pressure data, exhibits a pronounced peak at $v = 5/2$. The anisotropic resistance observed at $v = 5/2$, characterized by an extremely large ratio $R_{XX}/R_{YY} = 1.15$, signals the onset of a ground state which breaks rotational symmetry. The evolution of the magnetoresistance at $v = 5/2$, shown in Fig. 1, is therefore suggestive of a phase transition from a rotationally invariant FQHS, most likely a non-Abelian topological phase[16–18], to an anisotropic phase which breaks rotational symmetry. We note that in Fig. 1 resistance anisotropy develops not only at $v = 5/2$, but also at filling factors close to $v = 2.2$ and 2.8. However, in contrast to the anisotropy at $v = 5/2$, that at $v = 2.2$ and 2.8 is not sensitive to the temperature and it is commonly associated with geometric imperfections of the sample and of the contact placement[4]. This contrasting temperature dependence in our sample is shown in Fig. 2.

In 2DEGs with half-filled Landau levels we differentiate between two types of anisotropies: spontaneous and induced anisotropy. The ground states of the 2DEG associated with these anisotropies bear a close resemblance to the spontaneous and induced magnetism in an interacting spin system. In the absence of an externally applied magnetic field, the spin system exhibits spontaneous symmetry breaking which manifests in a sharp phase transition between the ordered ferromagnet and the disordered paramagnet. In contrast, the development of the ordered phase with the application of an external magnetic field is not associated with a thermodynamic singularity. In the 2DEG, spontaneous anisotropy develops in the absence of any externally applied symmetry-breaking fields at $v = 9/2, 11/2, 13/2, 15/2, \ldots$ (refs 3, 6), and also at $v = 7/2$ (ref. 30) at low enough temperatures. The ground state at these filling factors is the well-known quantum Hall nematic phase, also referred to in the literature as the stripe phase[12]. Contrary to the behaviour at the above filling factors, the ground state at $v = 5/2$ was always found to be isotropic in the absence of a symmetry-breaking field[4,6]. Induced anisotropy at $v = 5/2$ appears, however, with the application of an external symmetry-breaking field. An in-plane magnetic field at $v = 5/2$ induces a compressible nematic-like anisotropic phase[22–25] or an incompressible nematic FQHS (refs 26–28). Anisotropy also appears with the application of uniaxial strain, another symmetry-breaking field[41].

In contrast to these previous experimental results, the anisotropy we observe at $v = 5/2$ in Fig. 1c has clearly developed spontaneously. Indeed, because of the hydrostatic nature of the applied pressure, in our experiment the rotational symmetry in the plane of the 2DEG is not broken by any external fields. An unintentional in-plane magnetic field may appear in our experiment if the sample tilts inside the cell during the compression process generating the high pressures. However, the isotropic resistance near $v = 5/2$ at $P = 6.95$ and 7.60 kbar attests that this is not the case. We therefore report a pressure-tuned spontaneous transition at $v = 5/2$ from an isotropic FQHS to a quantum Hall nematic phase through an isotropic Fermi liquid phase. Because at $T = 12$ mK the isotropic liquid is observed in an extremely narrow range of pressures, our data are suggestive of a direct quantum phase transition from the FQHS to the nematic phase in the limit of zero temperatures.

From the point of view of the symmetry, both the FQHS-to-nematic and the paramagnet-to-ferromagnet transitions occur spontaneously. However, a notable difference between these two transitions is that in our data the collapse of the ordered nematic phase is accompanied by the emergence of a topologically ordered phase rather than a disordered isotropic phase. The FQHS-to-nematic transition we observe at $v = 5/2$ is thus an example of a phase transition which involves the change of both the topological as well as the rotational order across the transition. Such a phase transition was predicted in ref. 19. However, because of the boundary conditions used in this numerical work, which break the rotational symmetry, the stripe phase could not be distinguished from the nematic phase and the phase transition could not be characterized. Our observations are incompatible with a direct first-order phase transition from the FQHS to the nematic phase, but are compatible with either a direct continuous transition between these two phases or with an intercalation of an isotropic Fermi liquid between these two phases. In the former case we think that the quantum critical point is necessarily described by an exotic theory (not based on the Landau picture) owing to the interplay of the nematic order and the emergent topological order in the non-Abelian FQHS. We note that similar exotic transitions have been proposed in topologically ordered states[32] and in a generalized quantum dimer model[40].

The difference between the spontaneous and induced anisotropic phases at half-filled Landau levels is further highlighted by their contrasting magnetotransport signatures. Although both manifest in anisotropic magnetoresistance, a peculiarity of the spontaneous
anisotropy is that it develops over a limited span of filling factors \( \Delta \nu \simeq 0.15 \) centred on a half-integer filling factor\(^5,6\). In contrast, the resistance anisotropy induced by an external in-plane magnetic field at \( \nu = 5/2 \) is present over a considerably wider range of filling factors \( \Delta \nu \simeq 0.6 \) (refs 22–28). The observed anisotropy at \( P = 8.26 \) kbar shown in Fig. 1c, occurring over a narrow range of filling factors \( \Delta \nu \simeq 0.15 \), is consistent with our earlier conclusion that the ground state at \( \nu = 5/2 \) is a genuine quantum Hall nematic phase\(^5,6\), similar to that observed at \( \nu = 9/2 \) (refs 5,6).

The evolution of the two longitudinal resistances \( R_{XX} \) and \( R_{YY} \) is captured over a larger pressure range in the contour plot shown in Fig. 3. We focus on the behaviour along the line at \( \nu = 5/2 \). At low pressures the FQHS is shown as a narrow vertical blue line. As the pressure is increased, the \( \nu = 5/2 \) FQHS weakens and past a critical pressure, estimated to be \( P_C \simeq 7.8 \pm 0.2 \) kbar, the nematic phase is stabilized. The nematic phase is seen in Fig. 3 as a red island in \( R_{XX} \) and as a blue basin in \( R_{YY} \). Our data at \( \nu = 5/2 \), shown in Fig. 3, reinforce the possibility of a direct quantum phase transition from a FQHS to the nematic phase as the pressure is tuned through its critical value \( P = P_C \).

In Fig. 3 the region of stability for the nematic phase is centred near \( P \simeq 8.7 \) kbar. The nematic phase is weakened by a further increase in pressure until it disappears at an extrapolated value of \( P \simeq 10 \) kbar. Past this pressure, the resistance does not exhibit a strong anisotropy, thus the ground state past 10 kbar is a rotationally invariant, uniform electron fluid. At \( \nu = 5/2 \) we find a second quantum phase transition near \( P \simeq 10 \) bar between the nematic phase and an isotropic Fermi liquid. We note that in Fig. 3 we also see weak FQHSs at \( \nu = 7/3 \) and 8/3. However, the nematic phase is not stabilized at these filling factors.

We note that the orientation of the nematic phase relative to the crystal axes in experiments in the ambient is reproduced in different cooldowns\(^9,10\). Similarly, the orientation of the nematic phase at \( \nu = 5/2 \) observed in the range \( P \simeq 7.8–10 \) kbar in our experiment does not change after we change the pressure in our cell at room temperature. In the most general case one would expect the nematic order to develop along different crystal directions. However, in the GaAs host semiconductor the nematic phase interacts weakly with the host crystal. The origin of this weak interaction is not at present understood\(^5,6,33,34\). This interaction is, however, responsible for the alignment of the nematic phase with the crystal axes and renders the resistance anisotropy readily observable. Using the analogy of the nematic phase with the ferromagnetic phase in interacting spins, in the latter system one expects randomly oriented ferromagnetic domains unless a weak interaction with the crystal field aligns the magnetization of these domains. However, for both the spontaneously formed ferromagnetic and nematic phases, the presence of a weak interaction with the crystal is not required.

We now discuss possible origins for the observed isotropic FQHS-to-nematic phase transition. Pioneering numerical work found that a transition from the Pfaffian to a nematic phase occurs when the effective electron–electron interaction is tuned away from its Coulomb expression\(^11\). In this work the required interaction was generated by varying the layer width \( w \) of the 2DEG. The layer width appears in the theory in its adimensional form \( w/l_0 \), where \( l_0 = \sqrt{\hbar/eB} \) is the magnetic length. Later theoretical work addressed the evolution of the stability of the Pfaffian at \( \nu = 5/2 \) with \( w/l_0 \) (refs 35,36) and with the magnitude of a three-body interaction \( \kappa \)\(^2,13\). However, the lack of a spontaneously developed nematic phase at \( \nu = 5/2 \) in experiments at ambient pressures suggests that tuning of the layer width by itself is not sufficient to stabilize the nematic phase.

Landau level mixing, as measured by the Landau level mixing parameter \( \kappa \), also affects the effective electron–electron interaction\(^17\). Theory of the ground state at \( \nu = 5/2 \) in the \( k \cdot w/l_0 \) plane, however, has not considered an instability towards a nematic phase\(^38,42\). We think that, by tuning the pressure, we access a combination of \( \kappa \) and \( w/l_0 \), which in the spirit of ref. 19, stabilizes the nematic phase. A detailed discussion of the dependence on pressure of these parameters can be found in the Supplementary Information. Decreasing density with an increasing pressure\(^43\) has by far the strongest imprint on these values. We find that in the pressure range \( P = 8.26–9.76 \) kbar at which the nematic phase is detected, the density ranges between \( n = 1.0–0.68 \times 10^{11} \) cm\(^{-2} \); the Landau level mixing parameter spans \( \kappa = 2.08–2.57 \), and the adimensional layer width spreads over \( w/l_0 = 1.51–1.24 \). Simply put, the nematic phase in our experiment develops when the conditions \( \kappa > 2 \) and \( w/l_0 < 1.5 \) are simultaneously met. From a survey of the literature on electron samples we find that the above region of the \( k \cdot w/l_0 \) parameter space has not yet been accessed\(^35,39,40,45\). We thus think that either the combination of low enough \( w/l_0 \) and high enough \( \kappa \), or other yet unknown factors, are responsible for the appropriate short-range interactions needed for stabilizing the nematic phase at \( \nu = 5/2 \). Nonetheless, clarifying the stability conditions of the nematic phase at \( \nu = 5/2 \) needs further investigation, as this phase does not develop in p-doped samples with \( \kappa = 14.4 \) and \( w/l_0 = 1.1 \) (ref. 46) or \( \kappa = 20 \) and \( w/l_0 = 0.79 \) (ref. 47).
Finally, we note that the nematic phase we referred to is of electrons. We notice that at $P = 8.26$ kbar there is a weak FQHS present at $\nu = 8/3$ in the vicinity of the nematic phase. The presence of this weak FQHS signals the formation of composite fermions, thus there is an interesting possibility that anisotropy observed in Fig. 1c is due to a nematic phase of composite fermions.\(^\text{49}\)

Methods

Methods and any associated references are available in the online version of the paper.

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**Author contributions**

N.S., M.J.M. and G.A.C. conceived the experiment. G.C.G. and M.J.M. grew the GaAs/AlGaAs wafer. N.S. fabricated the sample. N.S., K.A.S. and G.A.C. performed the measurements and analysed the data. The manuscript was written by K.A.S. and G.A.C. with input from all authors and with critical contributions from E.F.

**Additional information**

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to G.A.C.

**Competing financial interests**

The authors declare no competing financial interests.
Methods
We measured a symmetrically doped \( w = 30 \text{ nm} \) wide \( \text{Al}_{0.24}\text{Ga}_{0.76}\text{As/GaAs/Al}_{0.24}\text{Ga}_{0.76}\text{As} \) quantum well sample\(^{49,50}\). The density measured at ambient pressures is \( n = 2.8 \times 10^{11} \text{ cm}^{-2} \) and the mobility is \( 15 \times 10^{6} \text{ cm}^{2} \text{ V}^{-1} \text{ s}^{-1} \). The high hydrostatic pressures were generated using a commercial pressure clamp cell (easyLab Technologies Ltd, model Pcell 30). Each incremental increase in the pressure was done at room temperature; pressures were measured both at room temperature as well as at low temperatures using different manometers. Pressures quoted throughout our paper, however, are the low-temperature pressures. The pressure cell also contained a small light-emitting diode which was used to illuminate the sample after every cooldown to prepare the state. We chose a sample size of lateral extent \( 2 \times 2 \text{ mm}^{2} \) so that it can easily fit inside the Teflon lining of the pressure cell.

As shown in Fig. 1, our square-shaped sample has four indium ohmic contacts on the corners of the square. The longitudinal resistance was measured using a standard low-frequency lock-in technique at an a.c. excitation of 2 nA.

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