Composite Fermions in the Quantum Hall Regime

J. K. Jain

Recent progress in the understanding of the two-dimensional electron system under the influence of a strong magnetic field is reviewed. This system is characterized by the existence of a particle called the composite fermion, which manifests itself in several dramatic experimental observations.

A priori, one might expect a liquid of interacting electrons to behave in a very complex manner. However, it often resembles a weakly interacting gas of particles different from electrons, which may be called the quasi-particles of the system. An identification of the precise nature of these quasi-particles is a primary goal; it not only provides back-of-the-envelope explanations for various qualitative features of the system but also makes us feel that we really understand it. A well-known example is that of interacting electrons in a normal conductor, which, as realized by Landau, behave like weakly interacting quasi-particles with the charge of an electron, e, obeying fermion statistics; this insight clarified the reason behind the surprising success of the free electron model. Perhaps more dramatic are "strongly correlated" electron systems, which are described in terms of noninteracting quasi-particles that are qualitatively different from electrons. A superconductor, for example, is loosely described as a weakly interacting gas of boson-like Cooper pairs of charge $2e$.

We consider a two-dimensional electron system (2DES) in the presence of a high transverse magnetic field, where several striking phenomena have been discovered during the last one and a half decades. In this case, the strongly correlated liquid of electrons is equivalent to a weakly interacting gas of particles called composite fermions. A composite fermion is an electron carrying an even number of vortices of the many-particle wave function, where a unit vortex is defined so that an electron acquires a phase of 2π upon traversing a closed loop around it. Several experimental properties of the 2DES in a range of high magnetic fields can be understood in a straightforward manner as a consequence of the formation of composite fermions (at still higher magnetic fields, electrons form a crystal, known as the Wigner crystal, and the composite fermion description is no longer applicable).

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The Quantum Hall Effect

We start with a brief introduction to the phenomenon of the quantum Hall effect (QHE). To appreciate its dramatic nature, it is necessary first to understand the classical Hall effect, discovered in 1879 (*1*). Consider a 2DES with electron density ρ and a current I_x flowing along the x direction. As a result of the Lorentz force, a potential difference V_y develops transverse to the current flow, and the corresponding resistance, the Hall resistance, is given by

$$R_{\mathrm{H}} \equiv \frac{V_y}{I_x} = \frac{B}{\rho e c} = \frac{h}{\nu e^2} \qquad (1)$$

where B is the magnetic field, c is the speed of light, h is Planck's constant, and ν is defined as

$$\nu = \frac{\rho h c}{eB} \qquad (2)$$

The Hall effect is routinely used to determine the type of carrier (electron or hole) and the carrier density.

Almost exactly a century after the discovery of the Hall effect, von Klitzing (*2*) observed that at high magnetic fields there were regions where the Hall resistance did not change as a function of the magnetic field and the longitudinal resistance was exponentially small, vanishing in the limit $T \rightarrow 0$, where T is temperature. The most remarkable aspect was that the Hall resistance on the plateaus was given by

$$R_{\mathrm{H}} = \frac{h}{fe^2} \qquad (3)$$

where f was found to be an integer; that is, R_{H} was completely determined by the fundamental constants h and e. This phenomenon was named the integer quantum Hall effect (IQHE). Shortly afterwards, Tsui, Stormer, and Gossard (*3*) observed a plateau with $f = 1/3$, which was the beginning of the fractional quantum Hall effect (FQHE). By now, a large number of fractions have been observed (Fig. 1). The prominent fractions appear in certain sequences; some of these are

$$f = \frac{n}{2n+1} = \frac{1}{3}, \frac{2}{5}, \frac{3}{7}, \ldots$$

$$f = \frac{n}{2n-1} = \frac{2}{3}, \frac{3}{5}, \frac{4}{7}, \ldots$$

$$f = \frac{n}{4n+1} = \frac{1}{5}, \frac{2}{9}, \frac{3}{13}, \ldots$$

$$f = \frac{n}{4n-1} = \frac{2}{7}, \frac{3}{13}, \frac{4}{15}, \ldots$$

All fractions with $f < 1$ have odd denominators. As in the IQHE, the longitudinal resistance in the plateau region is exponentially small.

The observation of a dissipationless flow of current in a disordered nonsuperconducting solid-state system, and of a Hall resistance that is independent of the sample material and geometry, is a truly remarkable effect. It tells us that electrons in the QHE regime behave in a highly cooperative but at the same time extremely simple manner. Clearly, some new physical principle is at work.

Theoretically, the quantum mechanical problem is defined by the many-body Hamiltonian

$$H = H_0 + V$$

$$= \sum_j \frac{1}{2m_e}\left[\mathbf{p}_j + \frac{e}{c}\mathbf{A}(\mathbf{r}_j)\right]^2 + \frac{1}{2}\sum_{j \neq k} \frac{e^2}{\epsilon r_{jk}} \qquad (4)$$

where H_0 is the kinetic energy of electrons in the presence of a constant external magnetic field, V is the (Coulomb) interaction energy, m_e is the band mass of an electron, $\mathbf{p}_j$ is the momentum of electron j, $\mathbf{A}$ is the magnetic vector potential at position $\mathbf{r}$, and ϵ is the dielectric constant of the background material (usually GaAs). The electrons are confined to the xy plane. The

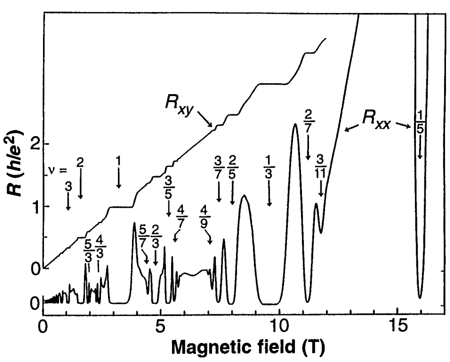

Fig. 1. A plot of the Hall and the longitudinal resistances, R_{xy} and R_{xx}. Note that the curves are offset. [Printed with permission (*31*)]

problem of a single electron in an external magnetic field was solved by Landau long ago (*4*). Its energy is quantized, given by

$$E_{n,l} = \left(n + \frac{1}{2}\right)\hbar\omega_c \qquad (5)$$

where $\hbar = h/2\pi$ and $\hbar\omega_c = \hbar eB/m_e c$ is the cyclotron energy. Levels with different n = 0, 1, 2, . . . are called the Landau levels (LLs). There are many states in each LL, with the degeneracy per unit area given by B/ϕ_0, where $\phi_0 = hc/e$ is the quantum of flux.

As usual, we start by asking how much can be explained if the Coulomb interaction is "switched off." Then, in the ground state, the electrons occupy the lowest energy single-particle states, with no more than one electron in each state, as required by the Pauli principle. The number of filled LLs is called the filling factor, given by $\nu = \rho\phi_0/B$. At integer filling factors, $\nu = n$, the ground state has n LLs completely occupied, and there is a gap of $\hbar\omega_c$ to excitations. It was shown by Laughlin (*5*) that such a gap is ultimately responsible for the IQHE. The precise argument requires a consideration of disorder (*5*) and is not repeated here. For the present purposes, it is taken for granted that the existence of a gap in the excitation spectrum of a disorderless system at $\nu = f$ results in a plateau with $R_H = h/fe^2$.

Because gaps are produced only at $\nu = n$ for noninteracting electrons, the full Hamiltonian with interactions must be considered for an explanation of the FQHE. The problem can be simplified by considering the limit $B \rightarrow \infty$, where the cyclotron energy is so large that the Coulomb interaction does not cause any LL mixing. In particular, for $\nu < 1$, electrons occupy only the lowest LL. Another simplification is that all electrons are fully polarized. The problem thus reduces to that of (effectively) spinless electrons confined to the lowest LL, with $H = V$ (the kinetic energy being an irrelevant constant equal to $\hbar\omega_c/2$ per electron).

An earlier attempt to explain the FQHE, the so-called quasi-particle hierarchy (QPH) approach, started with the work of Laughlin (*6*), in which he proposed an ansatz wave function to describe the correlated electron liquid at $\nu = 1/(2m + 1) = 1/3$, 1/5, 1/7, . . ., where m is an integer. It was compared by Laughlin (*6*) and others (*7*) with the exact numerical ground-state wave function of few electron systems and was found to be extremely accurate. Laughlin also constructed wave functions for the quasi-particle excitations and made compelling arguments that there was a finite gap, resulting in FQHE with $f = 1/(2m + 1)$. To explain the other fractions, Haldane (*8*) and Halperin (*9*) proposed iterative hierarchical schemes, which conjectured that "daughter" states occur when the quasi-particles of a "parent" state themselves form a Laughlin-like state. For example, 1/3 produced daughters at 2/5 and 2/7, which in turn generated 5/17, 3/11, 5/13, and 3/7, and so on. In this step-by-step manner, the QPH scheme allows for FQHE at all odd-denominator fractions starting from $f = 1/(2m + 1)$.

The QPH approach was somewhat speculative and not entirely satisfactory (*10*). The fact that a good description was available for $f = 1/(2m + 1)$ but not for the other fractions was puzzling; given the qualitative similarity of the observations of various fractions, one would have thought that once the origin of the FQHE was resolved, it should explain all fractions on a more or less equal footing. This indicated that the physics of the Laughlin wave function was itself not fully understood. There were several attempts to elucidate the relevant correlations in the Laughlin wave function. Girvin and MacDonald (*11*) related it, by a singular gauge transformation, to a boson wave function, which possessed algebraic off-diagonal long-range order. Zhang, Hansson, and Kivelson (*12*) and Read (*13*) proposed a mean field theory in which the Laughlin wave function was viewed as a Bose condensate. These theories, however, also did not shed any new light on the other fractions.

Composite Fermion Theory

The motivation of composite fermion theory (*14*) was to provide a unified description of the IQHE and the FQHE. Although they look qualitatively similar experimentally, the possibility of a relation between them had not been contemplated, mainly because the FQHE was believed to be fully explainable within the lowest LL, whereas the IQHE clearly required the higher LLs. One of the crucial steps of the composite fermion theory was to allow the formal use of higher LLs even in the discussion of the FQHE within the lowest LL.

The basic hypothesis of the composite fermion theory is that electrons in the lowest LL avoid each other most efficiently by capturing an even number ($2m$) of vortices of the wave function and transforming into composite fermions. It is further assumed that essentially all of the Coulomb interaction is exhausted in the creation of the composite fermions, so that the residual interaction between the composite fermions is relatively weak; in fact, they will be taken to be noninteracting for most purposes. Composite fermions move in an "effective" magnetic field, because the phases generated by the vortices partly cancel the Aharonov-Bohm phases originating from the external magnetic field. Because a vortex produces the same phase as a flux quantum (the Aharonov-Bohm phase associated with a closed loop encircling a flux quantum is also 2π), the composite fermions can be crudely viewed as electrons carrying $2m$ flux quanta, and the effective magnetic field B^* experienced by the composite fermions can be calculated by assuming that each electron has absorbed $2m$ flux quanta of the external magnetic field (Fig. 2). This yields

$$B^* = B - 2m\rho\phi_0 \qquad (6)$$

The effective field B^* can be either positive or negative. Equation 6 also implies a relation between the electron and composite fermion filling factors $\nu = \rho\phi_0/B$ and $\nu^* = \rho\phi_0/B^*$

$$\nu = \frac{|\nu^*|}{2m|\nu^*| \pm 1} \qquad (7)$$

Thus, the liquid of interacting electrons at B behaves like a gas of free composite fermions at B^*. The composite fermions can, in general, occupy several quasi-LLs even when electrons are strictly confined to their lowest LL. As we will see below, Eqs. 6 and 7 are sufficient for explaining most of the experimental observations.

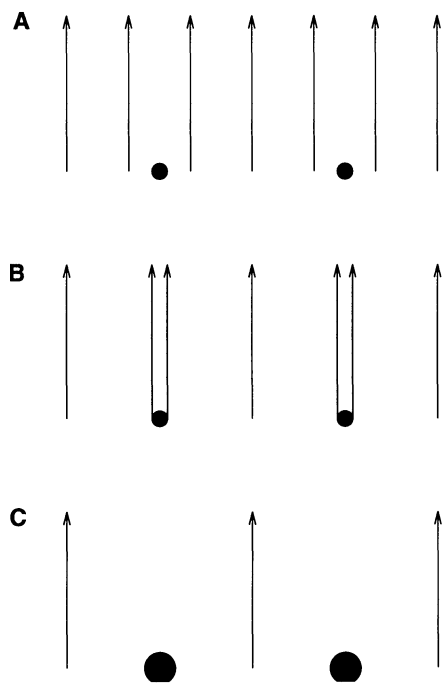

Fig. 2. (**A**) Electrons (dots) in a uniform magnetic field, with arrows representing magnetic flux quanta. (**B**) Each electron binds two flux quanta to become a composite fermion. Composite fermions do not see the flux bound to them and, as a result, experience a smaller effective magnetic field; this is clear in (**C**), where composite fermions are depicted as bigger dots.

Numerical Studies

The wave function of noninteracting composite fermions at ν^*, $\Phi_{\nu^*}^{\mathrm{CF}}$, is constructed simply by taking the known wave function of noninteracting electrons at ν^*, Φ_{ν^*}, and attaching $2m$ vortices to each electron

$$\Phi_{\nu^*}^{\mathrm{CF}} = \prod_{j<k} (z_j - z_k)^{2m} \Phi_{\nu^*} \tag{8}$$

Here $z_j = x_j + iy_j$ denotes the position of the jth particle, and multiplication by the Jastrow factor $\Pi_{j<k}(z_j - z_k)^{2m}$ attaches $2m$ vortices to each electron to convert it into a composite fermion (*15*). From the form of the wave function, it becomes intuitively clear why composite fermions might be formed as a result of the repulsive Coulomb interaction. Because of the Jastrow factor, the probability of finding two electrons close to each other in the state Φ^{CF} is very small: It is proportional to r^{4m+2} as the distance between the electrons $r \to 0$. Despite the use of the higher LL states, $\Phi_{\nu^*}^{\mathrm{CF}}$ is predominantly in the lowest LL (*16*), and its lowest LL projection is identified with the lowest LL wave function of interacting electrons at ν.

A fortunate feature of the FQHE problem is that it is possible to obtain numerically the exact solutions in the lowest LL for a finite number (typically 6 to 10) of electrons, which provides the opportunity for a rigorous and unbiased test of any theoretical ideas for the FQHE. The composite fermion theory has been compared with the exact solutions in great detail (*17–19*) and shown to be remarkably successful. It has been found that the low-energy states of interacting electrons at ν have the same quantum numbers as those of noninteracting fermions at ν^*, and their microscopic wave functions are well represented by the composite fermion wave functions of Eq. 8. In particular, filled quasi-LLs of composite fermions, $|\nu^*| = n$, relate to interacting electrons at $\nu = n/(2mn \pm 1)$. Here, the ground state of interacting electrons is separated from the other states by a gap, as expected from the analogy to the IQHE state at $|\nu^*| = n$. The composite fermion wave functions are essentially identical to the true ground-state wave functions (Table 1). Because the numerical states are exact and there are no adjustable parameters in the composite fermion theory, these studies make a compelling case that the low-energy dynamics of interacting electrons at ν are indeed well described in terms of free composite fermions at ν^*. For $\nu = 1/(2m + 1)$, which corresponds to one filled quasi-LL of composite fermions ($\nu^* = 1$), the composite fermion wave function is identical to Laughlin's wave function.

Table 1. Overlap of the lowest LL projection of $\Phi_{\pm n}^{\mathrm{CF}}$ with the corresponding exact lowest LL Coulomb wave function at $\nu = n/(2n \pm 1)$ (obtained numerically) for several values of n. The quantity N is the number of electrons. The wave functions have been properly normalized for the calculation of the overlap. Source (*7*) for 1/3, (*17*) for 2/5, and (*18*) for 3/7 and 2/3.

ν	n	N	Overlap
1/3	1	7	0.9964
		8	0.9954
		9	0.9941
2/5	2	6	0.9998
		8	0.9996
3/7	3	9	0.9994
2/3	−2	6	0.9965
		8	0.9982
		10	0.9940

The FQHE

The IQHE of composite fermions ($|\nu^*| = n$) translates into the FQHE of electrons at $\nu = n/(2mn \pm 1)$. These are precisely the observed sequences of fractions. Also, only odd-denominator fractions are obtained, in agreement with experiment. The analogy of the FQHE of electrons to the IQHE of composite fermions has been extended to several other aspects. In low-disorder samples, the transition from one plateau from another takes place at $\nu^* = n + 1/2$ (*20*), as predicted by the composite fermion theory (*21*). This also explains the relative widths of various plateaus in the limit $T \to 0$. Halperin *et al.* (*22*) interpreted the gaps of the $n/(2mn \pm 1)$ states as the effective cyclotron energy of composite fermions, given by $\hbar eB^*/m^*c$, where B^* is given by Eq. 6 and m^* is the effective mass of composite fermions. Du *et al.* (*23*) found the actual gaps to be consistent with this form (*24*). Leadley *et al.* (*25*) and Du *et al.* (*26*) have successfully analyzed the minima and maxima around $\nu = 1/2$ in terms of the Shubnikov–de Haas oscillations of composite fermions, in analogy to the Shubnikov–de Haas oscillations of electrons near $B = 0$. They found that the effective mass of composite fermions, for typical experimental systems, is roughly 50 to 100% of the electron mass (that is, about an order of magnitude larger than the electron band mass in GaAs), in general agreement with the mass obtained from the gap measurements (*23*). All of these facts provide support to the picture in which the FQHE of electrons is viewed as the IQHE of composite fermions. The FQHE results from the existence of composite fermions in the same way as the IQHE results from the existence of electrons, and the observation of the FQHE thus constitutes an observation of the composite fermions.

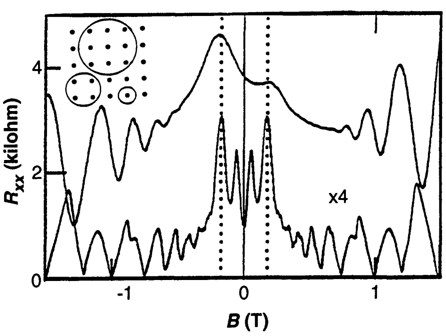

Fig. 3. The resistance of an antidot superlattice, shown in the inset, in the vicinity of $B = 0$ (lower curve) and $B^* = 0$ (upper curve). The scales for B and B^* differ by a factor of $\sqrt{2}$. The vertical dotted lines show the peaks corresponding to the smallest commensurate cyclotron orbit, enclosing only one antidot (see inset). The composite fermion peaks for other cyclotron orbits (for example, those enclosing four or nine antidots) are not seen presumably because of the relatively small mean free path of composite fermions. [Adapted from (*29*) with permission of Kang *et al.*]

Composite Fermi Sea

According to Eqs. 6 and 7, interacting electrons at $\nu = 1/(2m)$ (or $B = 2m\rho\phi_0$) are equivalent to noninteracting composite fermions at $\nu^* = \infty$ (or $B^* = 0$). It was not clear for some time if the composite fermion description remained valid here, but, motivated by certain experimental anomalies near $\nu = 1/2$ (*27*), Halperin, Lee, and Read (*22*) proposed that the state at $\nu = 1/2$ is a Fermi sea of composite fermions. It is analogous to the Fermi sea of electrons at $B = 0$, with the trivial difference that the composite fermions at $B^* = 0$ are fully spin-polarized, whereas the electrons at $B = 0$ are spin-unpolarized. As a result, the Fermi wave vector of composite fermions is $k_F^* = \sqrt{2}\, k_F$, where k_F is the Fermi wave vector of electrons at $B = 0$.

Three recent experiments (*28–30*) have confirmed the existence of composite fermions in the compressible region near $B^* = 0$ (that is, near $B = 2\rho\phi_0$) by observing the cyclotron motion of composite fermions. As the magnetic field is moved slightly away from $B^* = 0$, composite fermions are expected to execute a cyclotron orbit with radius $R^* = \hbar k_F^*/eB^*$. Because $k_F^* = \sqrt{2}k_F$, the cyclotron radius of composite fermions at B^* is equal to that of electrons at $B = B^*/\sqrt{2}$; therefore, the structures near $B = 0$ and $B^* = 0$ should look similar, provided they are plotted on scales differing by a factor of $\sqrt{2}$. Two of the experiments (*29*, *30*) were based on rather simple ideas. In one, Kang *et al.* (*29*) studied transport in antidot superlattices. The resistances near $B = 0$ and $B^* = 0$ are shown in Fig. 3. Near $B = 0$, peaks in the resistance occur when the cyclotron orbit is commensurate with

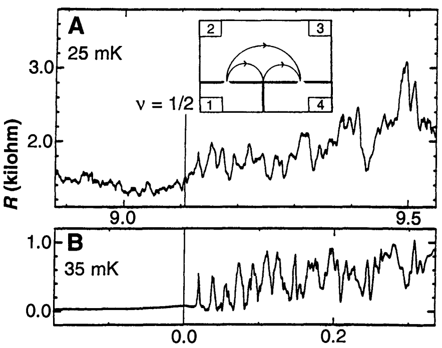

Fig. 4. The resistance $R = V_{34}/I_{21}$ for the magnetic focusing sample shown in the inset. (**A**) Focusing peaks of electrons near $B = 0$, and (**B**) focusing peaks of composite fermions near $B^* = 0$ (that is, near $\nu = 1/2$). The scales of B and B^* differ by a factor of about $\sqrt{2}$. A qualitative difference between the positive and negative B^* (that is, between $\nu > 1/2$ and $\nu < 1/2$) is evident, as is the one-to-one correspondence between several composite fermion and electron focusing peaks. [Reprinted from (*30*) with permission of Goldman *et al.*]

the lattice; some of the most relevant commensurate orbits are shown in the figure. Similar dimensional resonances of composite fermions show up near $B^* = 0$. Goldman *et al.* (*30*) observed magnetic focusing of composite fermions near $\nu = 1/2$. The experimental setup is shown in Fig. 4.; the current flows from 1 to 2, and the voltage is measured between 3 and 4. Near $B = 0$, a number of quasi-periodic peaks are observed (Fig. 4B), which occur at those values of B where the electrons coming straight out of the left constriction are focused into the right constriction, possibly after several specular reflections from the gate. Similar quasi-periodic structure was observed near $B^* = 0$ (Fig. 4A). The close correspondence between the electron and the composite fermion peaks is evident in both Figs. 3 and 4. These experiments confirm the existence of composite fermions in the compressible region near $\nu = 1/2$ by demonstrating that the dynamics of the charge carriers are described by the effective field B^* rather than the external field B. Thus, the composite fermion framework has not only provided a simple "one-step" explanation of the FQHE, it has also helped reveal the nontrivial nature of the metallic state at even-denominator fractions.

Conclusion

The following picture has finally emerged. First, electrons form LLs because of quantization of their kinetic energy. This results in the IQHE. Within the lowest LL, in a range of filling factor, electrons minimize their interaction energy by capturing vortices and transforming into composite fermions. Even though the composite fermions are quantum mechanical particles with a true many-body character, they may be treated, for most purposes, as ordinary noninteracting fermions moving in an effective magnetic field. They form quasi-LLs, execute cyclotron motion, and fill a Fermi sea. The formation of composite fermions lies at the root of the FQHE and several other fascinating experimental phenomena.

REFERENCES AND NOTES

1. E. H. Hall, *Am. J. Math* **2**, 287 (1879).
2. K. von Klitzing, G. Dorda, M. Pepper, *Phys. Rev. Lett.* **45**, 494 (1980).
3. D. C. Tsui *et al.*, *ibid.* **48**, 1559 (1982).
4. See L. D. Landau and E. M. Lifshitz, *Quantum Mechanics* (Addison-Wesley, Reading, MA, 1965), pp. 424–426.
5. R. B. Laughlin, *Phys. Rev. B* **23**, 5632 (1981).
6. ———, *Phys. Rev. Lett.* **50**, 1395 (1983).
7. For example, G. Fano, F. Ortolani, E. Colombo, *Phys. Rev. B* **34**, 2670 (1986); F. D. M. Haldane and E. H. Rezayi, *Phys. Rev. Lett.* **54**, 237 (1985).
8. F. D. M. Haldane, *Phys. Rev. Lett.* **51**, 605 (1983).
9. B. I. Halperin, *ibid.* **52**, 1583 (1984).
10. See J. K. Jain, *Adv. Phys.* **41**, 105 (1992).
11. S. M. Girvin and A. H. MacDonald, *Phys. Rev. Lett.* **58**, 1252 (1987).
12. S. C. Zhang *et al.*, *ibid.* **62**, 82 (1989).
13. N. Read, *ibid.*, p. 86.
14. J. K. Jain, *ibid.* **63**, 199 (1989).
15. To see how multiplication by the Jastrow factor attaches $2m$ vortices to each electron, fix all z_j in the Jastrow factor except z_1. As z_1 traverses in a closed loop around any other electron, it acquires a phase of $4m\pi$, that is, it sees $2m$ vortices on all other electrons.
16. N. Trivedi and J. K. Jain, *Mod. Phys. Lett. B* **5**, 503 (1991).
17. G. Dev and J. K. Jain, *Phys. Rev. Lett.* **69**, 2843 (1992).
18. X. G. Wu, G. Dev, J. K. Jain, *ibid.* **71**, 153 (1993); X. G. Wu and J. K. Jain, preprint.
19. E. H. Rezayi and A. H. MacDonald, *Phys. Rev. B* **44**, 8395 (1991); M. Kasner and W. Apel, *ibid.* **48**, 11435 (1993); E. H. Rezayi and N. Read, *Phys. Rev. Lett.* **72**, 900 (1994).
20. V. J. Goldman *et al.*, *Phys. Rev. Lett.* **65**, 907 (1990).
21. J. K. Jain, S. A. Kivelson, N. Trivedi, *ibid.* **64**, 1297 (1990).
22. B. I. Halperin, P. A. Lee, N. Read, *Phys. Rev. B* **47**, 7312 (1993).
23. R. R. Du *et al.*, *Phys. Rev. Lett.* **70**, 2944 (1993).
24. Also see, I. V. Kukushkin, R. J. Haug, K. von Klitzing, K. Ploog, *ibid.* **72**, 736 (1994).
25. D. R. Leadley *et al.*, *ibid.*, p. 1906.
26. R. R. Du, H. L. Stormer, D. C. Tsui, L. N. Pfeiffer, K. W. West, *Solid State Commun.* **90**, 71 (1994).
27. H. W. Jiang, H. L. Stormer, D. C. Tsui, L. N. Pfeiffer, K. W. West, *Phys. Rev. B* **40**, 12013 (1989); R. L. Willett *et al.*, *Phys. Rev. Lett.* **65**, 112 (1990).
28. R. L. Willett, R. R. Ruel, K. W. West, L. N. Pfeiffer, *Phys. Rev. Lett.* **71**, 3846 (1993).
29. W. Kang *et al.*, *ibid.*, p. 3850.
30. V. J. Goldman *et al.*, *ibid.* **72**, 2065 (1994).
31. V. J. Goldman, unpublished figure.
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The Sverdlovsk Anthrax Outbreak of 1979

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In April and May 1979, an unusual anthrax epidemic occurred in Sverdlovsk, Union of Soviet Socialist Republics. Soviet officials attributed it to consumption of contaminated meat. U.S. agencies attributed it to inhalation of spores accidentally released at a military microbiology facility in the city. Epidemiological data show that most victims worked or lived in a narrow zone extending from the military facility to the southern city limit. Farther south, livestock died of anthrax along the zone's extended axis. The zone paralleled the northerly wind that prevailed shortly before the outbreak. It is concluded that the escape of an aerosol of anthrax pathogen at the military facility caused the outbreak.

Anthrax is an acute disease that primarily affects domesticated and wild herbivores and is caused by the spore-forming bacterium *Bacillus anthracis*. Human anthrax results from cutaneous infection or, more rarely, from ingestion or inhalation of the pathogen from contaminated animal products (*1*). Anthrax has also caused concern as a possible agent of biological warfare (*2*).

Early in 1980, reports appeared in the Western press of an anthrax epidemic in Sverdlovsk, a city of 1.2 million people 1400 km east of Moscow (*3, 4*). Later that year, articles in Soviet medical, veterinary, and legal journals reported an anthrax outbreak among livestock south of the city in the spring of 1979 and stated that people developed gastrointestinal anthrax after eating contaminated meat and cutaneous anthrax after contact with diseased animals (*5–7*). The epidemic has occasioned intense international debate and speculation as to whether it was natural or accidental and, if accidental, whether it resulted from activities prohibited by the Biological Weapons Convention of 1972 (*8*).

In 1986, one of the present authors (M.M.) renewed previously unsuccessful re-