Observation of the fractional quantum Hall effect under hydrostatic pressure

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(Received 25 January 1990)

We report on the first observation of the fractional quantum Hall effect (FQHE) under hydrostatic pressure. The FQHE has been observed at a range of two-dimensional electron-gas densities, n_s, in a high-quality $Al_xGa_{1-x}As/GaAs$ heterostructure at temperatures between 0.28 and 1.2 K and at hydrostatic pressures of 1 bar, 1.4 kbar, 4.5 kbar, and 6.2 kbar. We observe an increase of the activation energies for the $\frac{5}{3}$ and $\frac{7}{5}$ fractional states with increasing pressure and a very strong enhancement of the $\frac{4}{3}$ state both in ρ_{xx} and in the gradient of the Hall resistance $B\,d\rho_{xy}/dB$.

Since the discovery of the fractional quantum Hall effect (FQHE) in 1982,[1] the main thrust of research in this field has been the determination of the energy gaps associated with fractional states, at particular filling factors, via the temperature dependence of the minima in ρ_{xx}.[2,3] There is at present a discrepancy between the theoretical values and the measured values of the energy gaps, the measured values being consistently lower than theory predicts.[4,2,5] As this discrepancy has been found experimentally to be reduced with increasing sample mobility,[6-8] it has been suggested that this discrepancy is due to disorder broadening of the energy levels. It would obviously be useful therefore to be able to vary the amount of disorder in a particular sample while being able to achieve the same carrier concentration and hence the same magnetic field at which a particular filling factor occurs. We have attempted to do this with the combined use of hydrostatic pressure and the persistent photoconductivity effect.

Recently, attention has been focusing on the spin configuration of fractional states and the possibility of spin-unpolarized states.[9,10] Also, an experimental probe of the fractional charges of the quasiparticles has been proposed,[9] based on the extrapolation of activation plots to $1/T=0$, and has been used to lend weight to the predictions of Laughlin[11] and Haldane[12] that the quasiparticle charge e^* is given by $\pm e/q$ (where the filling factor $\nu=p/q$). Clearly it would be useful to examine further whether the intercept values of activation plots are related to a fundamental quantity by seeing if they remain invariant under the application of pressure.

In this paper we present the first measurements to be reported on the FQHE under hydrostatic pressure. Clear FQHE signals were observed in the resistivity components ρ_{xx} and ρ_{xy} in a high-quality $Al_xGa_{1-x}As/GaAs$ heterostructure in magnetic fields up to 13 T and at temperatures between 0.28 and 1.2 K. A set of results at similar carrier concentrations, n_s, were compared for hydrostatic pressures of 1 bar, 1.4 kbar, 4.5 kbar, and 6.2 kbar.

To subject the sample to high hydrostatic pressures, a small pressure cell was used with petroleum spirit as the pressure-transmitting medium. The cell, manufactured by Unipress, was specifically designed to fit into the 20-mm-diam sample space of the ^{3}He system used for the experiments. Optical access to the inside of the cell was gained via a sapphire window and the pressure determined by an InSb manometer mounted inside the cell.

With the pressure cell immersed in the ^{3}He in the sample space of the insert, a minimum temperature of 280 mK was attainable. Thermometry was provided by calibrated germanium and Speer resistors with an estimated

TABLE I. Sample parameters as a function of pressure.

Pressure	n_s^{dark} (10^{11} cm^{-2})	n_s^{light} (10^{11} cm^{-2})	μ^{dark} (10^6 cm^{2}V^{-1}s^{-1})	μ^{light} (10^6 cm^{2}V^{-1}s^{-1})	$\sigma_{xx}(\frac{3}{2})$ (e^2/h)
1 bar	1.7	3.1	1.5	2.4	0.038
1.4 kbar	1.6	3.1	1.2	2.3	0.029
4.5 kbar	1.4	3.1	1.1	1.8	0.025
6.2 kbar	1.2	3.0	1.1	2.3	0.023

uncertainty of 10 mK. The germanium resistor, the primary source of thermometry, was mounted on the top of the pressure cell and was in thermal contact with it.

The sample used in our experiments was a high-quality $Al_xGa_{1-x}As/GaAs$ heterostructure grown at Philips Research Laboratories (Redhill).[13] A Hall-bar geometry was used with six potential probes. The channel width was 75 μm and the longitudinal distance between the voltage probes used was 750 μm. Measurements were made with dc current densities of 27 μA/cm ($P=1$ bar, 1.4 kbar, 4.5 kbar) and 34 μA/cm ($P=6.2$ kbar) within the sample. Wires from voltage probes on the sample were fed to individual precision unity-gain buffer amplifiers and then to a scanner. With the output of the scanner attached to a digital voltmeter, measurements of the two longitudinal voltages and the two Hall voltages were facilitated. The data-acquisition process took 1 s to measure this set of voltages and was fully computer controlled. By recording two pairs of longitudinal and two pairs of transverse voltages, we were able to check for sample inhomogeneities.

The values of the carrier concentration and of the mobility of the sample are listed in Table I for the four different pressures applied. The table shows the values with no illumination "dark" and the maximum values obtainable, without inducing parallel conduction in the $Al_xGa_{1-x}As$, following illumination of the sample with a red-light-emitting-diode (LED) "light." At pressures of 1 bar and 1.4 kbar, parallel conduction could be induced in the $Al_xGa_{1-x}As$ layer with prolonged illumination of the sample. However, at pressures of 4.5 and 6.2 kbar there was no parallel conduction evident in the magnetoresistance of the sample, even after continuous illumination with a red LED operating near to base temperature for 0.5 h.

Sweeps to maximum field were made at a number of temperatures between 0.28 and 1.2 K at a range of n_s values following illumination using the persistent-photoconductivity effect. Figure 1 shows ρ_{xx} and ρ_{xy} at base temperatures and pressures of 1 bar, 1.4 kbar, 4.5 kbar, and 6.2 kbar at similar n_s values, a little below the value at which parallel conduction occurs at atmospheric pressure.

In all sets of data a strong $\frac{5}{3}$ state and a weaker developing $\frac{7}{5}$ state are apparent. The striking difference between the four sets of results is the apparent enhancement of the $\frac{4}{3}$ state when the pressure is increased from 1 bar through to 6.2 kbar. Supporting evidence is obtained from the ρ_{xy} plot, where there is clear evidence for a $\frac{4}{3}$ plateau at pressures of 4.5 and 6.2 kbar. We find that the information in the ρ_{xy} plot is most clearly demonstrated by evaluating the derivative $B\,d\rho_{xy}/dB$ as in Fig. 2, where the results at 1 bar, 1.4 kbar, 4.5 kbar, and 6.2 kbar are presented. The differentiation was performed numerically on the raw data, the result being smoothed by a Fourier-transform filter. As pointed out by Chang and Tsui,[14] there is a remarkable similarity between the diagonal resistivity, ρ_{xx}, and $B\,d\rho_{xy}/dB$. It has been found that weak features in ρ_{xx} are enhanced in $B\,d\rho_{xy}/dB$.[15] We find this to be the case also for our re-

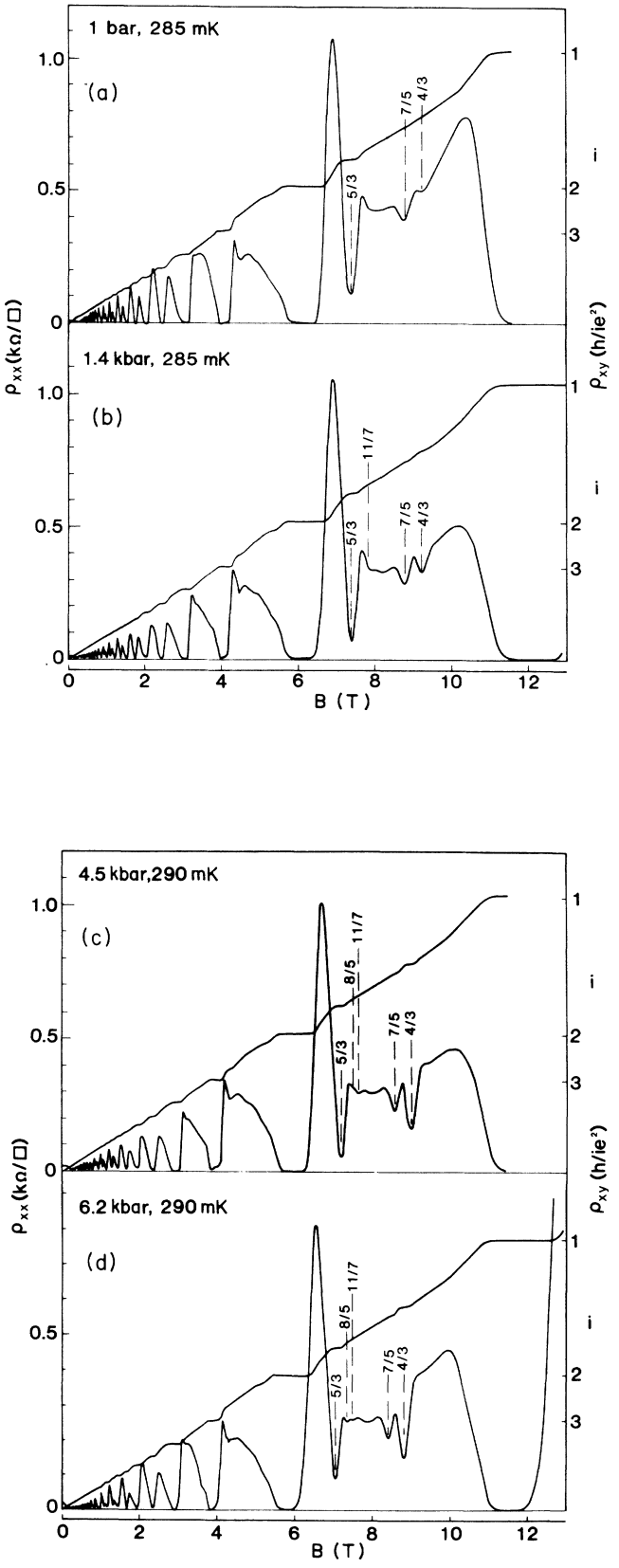

FIG. 1. ρ_{xx} and ρ_{xy} as a function of magnetic field showing enhancement of the $\frac{5}{3}$, $\frac{7}{5}$, and $\frac{4}{3}$ fractional states with increasing pressure: (a) 1 bar, (b) 1.4 kbar, (c) 4.5 kbar, and (d) 6.2 kbar.

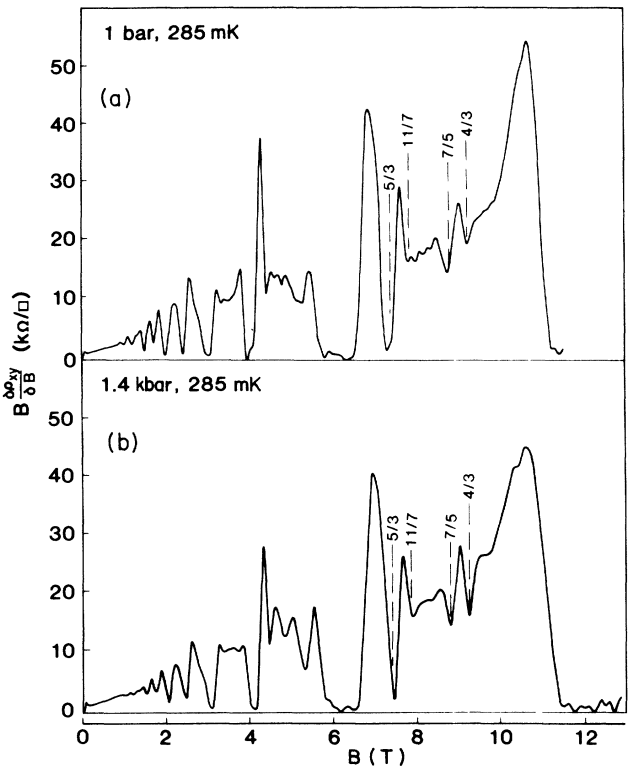

FIG. 2. Product of the differential of ρ_{xy} with respect to the magnetic field, $d\rho_{xy}/dB$, and of the magnetic field, B, showing enhancement of the $\frac{5}{3}$, $\frac{7}{5}$, and $\frac{4}{3}$ fractional states with increasing pressure: (a) 1 bar, (b) 1.4 kbar, (c) 4.5 kbar, and (d) 6.2 kbar.

sults. It can be seen from Fig. 2 that although there is only a small minimum in ρ_{xx} at a filling factor of $\frac{4}{3}$ at 1 bar, there is much clearer evidence for a minimum corresponding to the $\frac{4}{3}$ state in $B\,d\rho_{xy}/dB$. As with ρ_{xx}, the depth of the $\frac{4}{3}$ minima in $B\,d\rho_{xy}/dB$ seems to increase with increasing pressure. A slight difference between the carrier concentration given by the Hall resistance and the periodicity of the Shubnikov–de Hass oscillations has been taken into account in the labeling of Fig. 2.

Using the results in Fig. 1 and higher-temperature data, an activation analysis has been performed. As in Ref. 9, we assume that the temperature variation of the minima in the longitudinal resistivity follows

$$\rho_{xx}(T)=\rho_{xx}^{c}e^{-W/kT}, \tag{1}$$

where W is the energy gap between the fractional ground state and extended states of the quasiparticle excitations. In Fig. 3 we show the $\ln(\rho_{xx})$-versus-$(1/T)$ plots at pressures of 1 bar, 1.4 kbar, 4.5 kbar, and 6.2 kbar. From the slope of the linear region of the plots, we determine W, and, from the intercept, ρ_{xx}^{c}.

The activation energies for the $\frac{5}{3}$, $\frac{7}{5}$, and $\frac{4}{3}$ states are shown in Table II along with the values of ρ_{xx}^{c} and σ_{xx}^{c}.

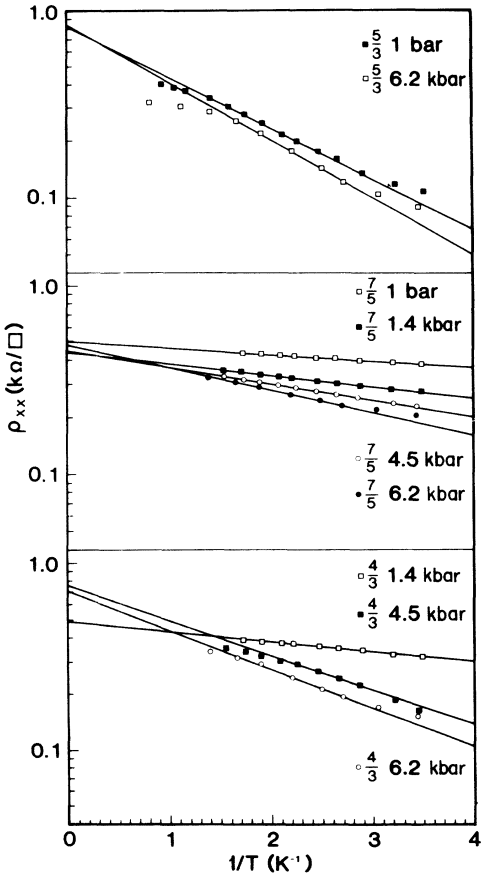

FIG. 3. Activation plots for the $\frac{5}{3}$, $\frac{7}{5}$, and $\frac{4}{3}$ states showing increases in the activation energies with increasing pressure.

TABLE II. Activation energies as a function of pressure for various fractional states. ρ_{xx}^c and σ_{xx}^c are defined in the text.

State	Pressure	B (tesla)	W (mK)	ρ_{xx}^c ($\Omega/\square$)	σ_{xx}^c (e^2/h)
$\frac{5}{3}$	1 bar	7.36	620±20	810±20	(0.79±0.02)/9
	1.4 kbar	7.42	863±19	1089±45	(1.05±0.04)/9
	4.5 kbar	7.23	888±13	1198±40	(1.16±0.04)/9
	6.2 kbar	7.04	710±40	830±70	(0.81±0.07)/9
$\frac{7}{5}$	1 bar	8.75	81±3	515±5	(0.98±0.01)/25
	1.4 kbar	8.80	147±13	455±15	(0.86±0.03)/25
	4.5 kbar	8.62	203±10	461±11	(0.88±0.03)/25
	6.2 kbar	8.41	278±10	508±20	(0.96±0.04)/25
$\frac{4}{3}$	1 bar	9.22			
	1.4 kbar	9.24	128±34	503±38	(0.31±0.02)/9 or (0.86±0.05)/25
	4.5 kbar	9.03	428±44	770±87	(0.48±0.04)/9 or (1.33±0.11)/25
	6.2 kbar	8.80	480±30	710±50	(0.44±0.03)/9 or (1.22±0.08)/25

However, the $\frac{4}{3}$ state at a pressure of 1 bar was not sufficiently pronounced to facilitate an activation analysis in the temperature range studied and is therefore not included in the table. The errors in the table reflect the effects of different choices of data points for the linear region of the activation plots.

In the sample studied, the activation energies of the $\frac{5}{3}$, $\frac{4}{3}$, and $\frac{7}{5}$ states at 1 bar increased with increasing magnetic field [in the carrier concentration range $(0.24-0.31)\times10^{12}$ cm^{-2}], quite markedly in the case of the $\frac{5}{3}$ state. At 6.2 kbar, where the carrier concentration is somewhat lower than for the other three pressures, one expects the activation energies to be lower than if obtained at the somewhat higher values of magnetic field observed at the other pressures. With this in mind, the activation data are not inconsistent with a small increase in the activation energy of the $\frac{5}{3}$ state, a stronger increase for that of the $\frac{7}{5}$, state and a very pronounced increase in the activation energy of the $\frac{4}{3}$ state with increasing pressure in the carrier-concentration range studied.

Clark *et al.* have made an extensive study of activation data for very-high-mobility samples[16,9] and have used the intercepts in Arrenhius plots as a probe of the fractional charge of the quasiparticles associated with fractional states. They extract σ_{xx}^c from the relationship

$$\sigma_{xx}^c=\sigma_{xx}(1/T=0)=\rho_{xx}^c/[(\rho_{xx}^c)^2+(\rho_{xy})^2]\ , \qquad (2)$$

using the measured values of ρ_{xx}^c and the calculated values of ρ_{xy}. Clark *et al.* assume that $\sigma_{xx}^c=C(e/q)^2/h$, where q is the denominator of the fractional filling factor, and find an average value of C of 0.91±0.11 for 13 fractional states.

In Table II we also show the values of σ_{xx}^c obtained from our data, following the method outlined above, using $q=3$ as expected for the $\frac{5}{3}$ state and $q=5$ as expected for the $\frac{7}{5}$ state. We observed that extrapolating σ_{xx}^c directly by inverting the resistivity tensor formed from the measured values of ρ_{xx} and ρ_{xy} at each value of $1/T$ gave very similar results. It can be seen from Table II that there is some variation in the value of C for the $\frac{5}{3}$ and $\frac{7}{5}$ states when the pressure is varied, but on the whole the agreement between our results and those of Clark *et al.* for the $\frac{5}{3}$ and $\frac{7}{5}$ states is quite good. This suggests that the intercept could indeed be related to a fundamental quantity that is invariant under the application of hydrostatic pressure. To test this hypothesis further, however, higher-pressure results are needed. Experiments along these lines are planned for the future.

The situation for the $\frac{4}{3}$ state is a little more complex, as is seen from the fact that the value of C with $q=3$, as expected for the $\frac{4}{3}$ state, is nowhere near 0.91±0.11 for all pressures. It can be seen from Table II that using a value of $q=5$ leads to a better agreement with this value of C for pressures of 1.4, 4.5, and 6.2 kbar, although there is a fairly large spread in its value.

The reason for this discrepancy could possibly be due to a magnetic-field-dependent transformation of the quasiparticle fractional charge from $\pm e/3$ to $\pm e/5$, of the type reported by Clark *et al.*,[19] but our results are somewhat inconclusive on this point. It is possible that for the $\frac{4}{3}$ state the temperature range used was not sufficiently low enough to enter into the activated regime, which would explain the seemingly low values of C, but this is considered unlikely. However, if this were the case the listed activation energies for the $\frac{4}{3}$ state would represent lower limits on the actual values.

To attempt to explain fully the impact of pressure on the FQHE, a number of effects have to be considered. The variation of the effective mass m^* for GaAs with pressure has been found to be well described by the

empirical formula[17]

$$m^*(P)/m^*(0)=1+(0.006\,15\pm0.000\,15)P(\text{kbar})\ , \quad (3)$$

and the variation of the dielectric constant ϵ of GaAs by[16]

$$\frac{d\ln[\epsilon(P)]}{dP}=-0.001\,73\pm0.000\,045\ \text{kbar}^{-1}\ . \quad (4)$$

Thus, upon application of a pressure of 6.2 kbar the effective mass in bulk GaAs will increase by about 3.8%, while the dielectric constant will decrease by about 1.07%.

Assuming complete polarization of the fractional states, the energy gaps associated with the FQHE are expected to be purely Coulombic in origin and therefore inversely proportional to the dielectric constant of the background material, i.e.,

$$W=ce^2/2\epsilon l\ , \quad (5)$$

where the magnetic length $l=(\hbar/Be)^{1/2}$ and where c is a proportionality constant for a particular fractional state. Thus, for a given state, and assuming complete polarization, a decrease in the dielectric constant would lead to an increase in the energy gap within this framework. However, application of a pressure of 6.2 kbar can only be expected to increase the energy gap by about 1.07%. This is not enough to account for the increased activation energies observed.

As mobility is inversely proportional to the effective mass, application of pressure will tend to reduce mobility. In our high-quality heterostructure the limiting factor on the mobility, at low temperatures, is thought to be ionized-impurity scattering from remote donors. The momentum relaxation time, τ_{ri}, due to the remote donors, being proportional to ϵ^2, will thus also lead to a reduction in mobility with pressure. These effects on the zero-field mobility are, however, small, as can be seen by comparing the measured mobilities of the sample at 1 bar, 1.4 kbar, 4.5 kbar, and 6.2 kbar at $B=0$ T. The small differences between the zero-field mobilities of the sample at different pressures, for comparable carrier concentrations, do not necessarily, however, preclude a change in the disorder potential fluctuation ($\approx h/\tau$) as being a reason for the apparent enhancement of the fractional states. The presence of a magnetic field can change the scattering mechanisms and, hence, τ.[18]

In the scaling model of the FQHE,[19] it is the value of σ_{xx} at a given filling factor that determines if a particular heirachy can be observed, the value of σ_{xx} having to lie beneath a given mobility fixed point for this to be possible. Thus as a measure of the effects of disorder on our sample in the presence of a magnetic field, the value of σ_{xx} at base temperature and at a filling factor of $\frac{3}{2}$ (the value at this filling factor being relatively insensitive to temperature) is also shown in Table I at the carrier-concentration values used for the activation plots. The value of σ_{xx} at a filling factor of $\frac{3}{2}$ is used, as no fractional state is observable in our sample at this filling factor, and as it is midway between the states being studied. As can be seen, this value decreases markedly with increasing pressure, for the data under consideration, which seems to suggest a reduction in disorder with increasing pressure in this sample at the carrier concentration used. This reduction in σ_{xx} with increasing pressure is equivalent to a reduction in ρ_{xx} as $\sigma_{xx}=\rho_{xx}/(\rho_{xx}^2+\rho_{xy}^2)$ and $\rho_{xy}\gg\rho_{xx}$.

A reduction of disorder in this way could account for the measured increase in the activation energies of the fractional states observed due to a reduction in the disorder broadening of the energy levels. This hypothesis would explain the presence of the developing states at $\frac{8}{5}$ and $\frac{11}{7}$ at base temperature and at a pressure of 6.2 kbar, while no such states are observable at base temperature while at a pressure of 1 bar. It is interesting to speculate that higher-order states may be brought out further with the application of even higher pressures. Future experiments are planned to see if this is so.

In conclusion, we have found that studying the FQHE in a high-mobility, two-dimensional electron gas under hydrostatic pressures provides interesting information which is complementary to that obtained by sample rotation and temperature or B-field variation. The intercepts of the activation plots for the $\frac{5}{3}$ and $\frac{7}{5}$ states do not appear to vary greatly, at the n_s values studied, as the pressure is increased through to 6.2 kbar. This supports the claim by Clark *et al.* that the intercept is related to a fundamental quantity.[9,16]

We have some evidence that W is slightly increasing with pressure for the $\frac{5}{3}$ state, is more significantly increasing for the $\frac{7}{5}$ state, and is greatly increasing with pressure for the $\frac{4}{3}$ state. The reason for the increase of the activation energies for these fractional states is not completely clear at present, although the size of the change seems to preclude an increase in the effective mass or a decrease in the dielectric constant of GaAs with increasing pressure as being the sole reasons since the effects of these changes are expected to be small at 6.2 kbar. It seems more likely that the increase in W with pressure is related to a reduction in the amount of disorder in the sample and hence to a reduction in the disorder broadening of the energy levels.

ACKNOWLEDGMENTS

We wish to acknowledge Dr. A. MacKinnon for useful discussions, Dr. R. G. Clark for helpful advice, and Professor R. A. Stradling for his support. We are grateful to the University of London, Central Research Fund for financial support.

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