Final Report for Period: 03/2008 - 02/2009 **Submitted on:** 05/25/2009
Principal Investigator: Pinczuk, Aron . **Award ID:** 0352738
Organization: Columbia University
Submitted By:
Pinczuk, Aron - Principal Investigator
Title:
Electron Liquids in Semiconductor Quantum Structures

Project Participants

Senior Personnel

Name: Pinczuk, Aron
Worked for more than 160 Hours: Yes
Contribution to Project:
Aron Pinczuk directs and oversees project research.

Name: Stormer, Horst
Worked for more than 160 Hours: Yes
Contribution to Project:
Horst Stormer directs and oversees project research.

Name: Gallais, Yann
Worked for more than 160 Hours: Yes
Contribution to Project:

Post-doc

Name: Gervais, Guillaume
Worked for more than 160 Hours: No
Contribution to Project:

Name: Jiang, Zhigang
Worked for more than 160 Hours: Yes
Contribution to Project:

Graduate Student

Name: Kirschenmann, Thomas
Worked for more than 160 Hours: No
Contribution to Project:

Name: Tan, Y.-W.
Worked for more than 160 Hours: No
Contribution to Project:

Name: Yan, J.
Worked for more than 160 Hours: No
Contribution to Project:

Name: Henriksen, Erik
Worked for more than 160 Hours: Yes

Contribution to Project:

Name: Yang, Xiuyuan
Worked for more than 160 Hours: Yes
Contribution to Project:

Name: Rhone, Trevor
Worked for more than 160 Hours: Yes
Contribution to Project:
Fully involved in the research supported by this grant. Received other support from NSF Nanoscale Science and Engineering Center at Columbia University.

Undergraduate Student

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Organizational Partners

Other Collaborators or Contacts

Kirk Baldwin, Bell Laboratories, Alcatel-Lucent , Murray Hill, NJ
Israel Bar Joseph, Weizmann Institute of Science, Rehovot, Israel
Kirill Bolotin, Columbia University, New York, NY
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Irene Dujovne, Delft University of Technology, Delft, The Netherlands
Yann Gallais, University of Paris 7, Paris, France
Sarah Goler, Columbia University, New York, NY
Javier Groshaus, Columbia University, New York, NY
Melinda Y. Han, Columbia University, New York, NY
Erik Henriksen, Columbia University, New York, NY
Cyrus F. Hirjibehedin, IBM Almaden Research Center, San Jose, CA
Pablo Jarillo-Herrero, Columbia University, New York, NY
Zhigang Jiang, Dept of Physics, Columbia University, New York, NY
Sokratis Kalliakos, Scuola Normale Superiore, Pisa, Italy
Biswajit Karmakar, Scuola Normale Superiore, Pisa, Italy
Philip Kim, Columbia University, New York, NY
Igor V. Kukushkin, Institute of Solid State Physics, Chernogolovka, Russia
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Cesar Pascual Garcia, Scuola Normale Superiore, Pisa, Italy
Vittorio Pellegrini, Scuola Normale Superiore, Pisa, Italy
Loren N. Pfeiffer, Bell Laboratories, Alcatel-Lucent, Murray Hill, NJ
Paulina Plochocka, Weizmann Institute of Science, Rehovot, Israel
Trevor D. Rhone, Columbia University, New York, NY
Mollie E. Schwartz, Columbia University, New York, NY
Y.-W. Tan, Columbia University, New York, NY
Dan Tsui, Princeton University, Princeton, NJ
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Alexander Van'kov, Institute of Solid State Physics, Chernogolovka, Russia
Theresa Villarson, Columbia University, New York, NY

Ken W. West, Bell Laboratories, Alcatel-Lucent, Murray Hill, NJ
Yong-Xie Wang, NHMFL, Tallahassee, FL
J.S. Xia, NHMFL, Gainesville, FL
Jun Yan, Columbia University, New York, NY
Xiuyuan Yang, Columbia University, New York, NY
Yuanbo Zhang, Columbia University, New York, NY

Activities and Findings

Research and Education Activities:

The groups led by Stormer and Pinczuk have focused this project on goals that seek the elucidation of novel many-particle effects that emerge in two-dimensional electron systems (2DES) as the result from fundamental quantum interactions. This experimental research is conducted under extreme conditions of temperature and magnetic field.

From the materials point of view, the ultra-high mobility systems in GaAs/AlGaAs quantum structures continue to be at the forefront of this research. The newcomer materials are based on graphene, a single atomic layer of graphite. The graphene research is attracting enormous attention from many communities involved in condensed matter research.

The investigated many-particle phenomena include the integer and fractional quantum Hall effect, composite fermions, and Dirac fermions, and a diverse group of electron solid and liquid crystal phases. The Stormer group performed magneto-transport experiments and far-infrared spectroscopy, while the Pinczuk group explores manifestations of such phases in optical spectra.

Professors Stormer and Pinczuk had extensive participation in research and training activities at Columbia University. These activities range from teaching undergraduate and graduate courses in condensed matter physics and nano science, participation in REU programs and a multitude of activities linked to research and general education of undergraduates, graduates and postdocs. In particular, Professor Stormer is a member of a group of 11 science professors at Columbia, who have changed the core curriculum. They have introduced a Frontiers of Science course that is now mandatory for ALL Columbia freshmen. Stormer teaches quantum mechanics, nano science and lower dimensional electron physics in this course to all Columbians; not just to the scientists. Pinczuk and Stormer are giving many talks at universities throughout the year.

Research Training

During the past five years the following graduate students and postdocs have received support from this grant:

Irene Dujovne, Dept. of Appl. Physics & Appl. Mathematics, Columbia University. She was a postdoc at the Delft University of Technology in The Netherlands, and now she is seeking employment in the US.
Yann Gallais, Dept. of Appl. Physics & Appl. Mathematics and Dept. of Physics,
Columbia University. He is now Assistant Professor at the University of Paris, France.
Guillaume Gervais, Dept of Physics, Columbia University, He is now Assistant Professor at McGill University, Montreal, Canada.
Erik Henriksen, Dept of Physics, Columbia University, New York, NY. He is now a postdoc at Caltech.
Javier Groshaus, Columbia University, New York, NY. He is now at the University of Toronto, Canada.
Cyrus Hirjibehedin, Dept of Physics, Columbia University. Cyrus graduated in September 2004. He is now a Lecturer at University College, London, UK.
Zhigang Jiang, Dept of Physics, Columbia University, New York, NY. He is now a postdoc at the University of California at Berkeley.
Thomas Kirschenmann, Dept. of Appl. Physics & Appl. Mathematics, Columbia. University. He is now at the University of Texas (Austin).
Trevor D. Rhone, Dept of Physics, Columbia University, New York, NY.
Y.-W. Tan, Dept. of Physics, Columbia University, New York, NY. She is now a postdoc at the Univ. of California at Berkeley.
Xiuyuan Yang, Dept of Physics, Columbia University, New York, NY.

The following undergraduate students have participated in research activities supported by this grant

Sarah Goler, Columbia University, New York, NY
Mason Jiang, Columbia University, New York, NY

Mollie Schwartz, Columbia University, New York, NY
Kenneth Sikes, Columbia University, New York, NY
Maika Takita, Barnard College, New York, NY
Theresa Villarson, Columbia University, New York, NY

The following graduate students and postdocs also participated in the research activities supported by this grant

Sokratis Kalliakos, Scuola Normale Superiore, Pisa, Italy.
Biswajit Karmakar, Scuola Normale Superiore, Pisa, Italy
Stefano Luin, Scuola Normale Superiore, Pisa, Italy.
Cesar Pascual Garcia, Scuola Normale Superiore, Pisa, Italy.
Paulina Plochocka, Weizmann Institute of Science, Rehovot, Israel.
Trevor David Rhone, Dept of Physics, Columbia University, New York, NY
Achinthya Singha, Scuola Normale Superiore, Pisa, Italy.
Alexander B. Van'kov, Institute of Solid State Physics, Chernogolovka, Russia
Theresa Villarson, Dept of Physics, Columbia University, New York, NY
Jun Yan, Dept of Physics, Columbia University, New York, NY

Professor Pinczuk participated in the Research Training Network on Collective Electronic States in Nanostructures (RTN COLLECT) that is sponsored by the Human Potential Program of the Research Directorate of the European Commission. The participation of Professor Pinczuk's group is supported by NSF through Supplement CHE-0241145. Cyrus Hirjibehedin, T. Kirschenman, Trevor Rhone and Sarah Goler received support from this program. The other institutions in RTN-COLLECT were: University of Cambridge (UK), Technical University of Munich (Germany), Scuola Normale Superiore (Italy), Universidad Aut¾noma of Madrid (Spain), Linkoping University (Sweden), University of Texas (Austin), and University of Copenhagen (Denmark). Pinczuk also collaborates with the group of Professor Igor V. Kukushkin of the Institute of Solid State Physics in Chernogolovka (Russia). Support for the collaboration with Russian colleagues is from the Civilian Research Development Foundation (CRDF), an Agency of the US Government.

Outreach Activities

Pinczuk and Stormer are participating actively in many of the out-reach activities associated with the local MRSEC and NSEC centers. During 2008 Stormer has given numerous talks on the subject of lower-dimensional electron physics and nano structures to high school students and to the general public, as well as at predominantly minority serving institutions.

Findings:

Inelastic light scattering experiments in the Pinczuk group create novel insights by looking at quantum fluid excitations in the integer and fractional quantum Hall regimes. Links with activated magneto-transport experiments in the Stormer group created novel insights on the roles of spin and charge degrees of freedom the states that manifest fractional quantum Hall liquids. Light scattering methods are shown to uncover properties of the exotic collective states that are not immediately apparent in magneto-transport measurements. In quantum liquids of higher Landau levels in ultra-high mobility 2D electron systems in GaAs/AlGaAs quantum structures we found intriguing and surprising roles of the spin degree of freedom These findings defy current conventional wisdom. They are described in this report on the section Contributions within Discipline.

In graphene single layers and bilayers the collaboration between the Stormer and Kim groups at Columbia has uncovered remarkable novel behaviors that include the observation of the quantum Hall effect at room temperature, the first cyclotron resonance experiments on single and bilayer graphene, and the achievement of record carrier mobility in suspended single layers of graphene. These findings were extensively described in the section Contributions within Discipline of the report we filed with NSF in February 2008.

Training and Development:

During the past five years the following graduate students and postdocs have received support from this grant:

Irene Dujovne, Dept. of Appl. Physics & Appl. Mathematics, Columbia University. She was a postdoc at the Delft University of Technology in

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Columbia University. He is now Assistant Professor at the University of Paris, France.
Guillaume Gervais, Dept of Physics, Columbia University, He is now Assistant Professor at McGill University, Montreal, Canada.
Erik Henriksen, Dept of Physics, Columbia University, New York, NY. He is now a postdoc at Caltech.
Javier Groshaus, Columbia University, New York, NY. He is now at the University of Toronto, Canada.
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Outreach Activities:

Outreach Activities

Pinczuk and Stormer are participating actively in many of the out-reach activities associated with the local MRSEC and NSEC centers. During 2007 Stormer has given numerous talks on the subject of lower-dimensional electron physics and nano structures to high school students and to the general public, as well as at predominantly minority serving institutions. He has given a plenary lecture at New York City's Nano-Day to ~500 high school students.

Journal Publications

S. Kalliakos, V. Pellegrini, C. P. Garcia, A. Pinczuk, B. S. Dennis, L. N. Pfeiffer, K. W. West, "Optical Control of Energy-level Structure of few Electrons in AlGaAs/GaAs Quantum Dots", Nano Letters, p. 577, vol. 8, (2008). Published,

Y. Gallais, J. Yan, A.Pinczuk, B.S. Dennis, L.N. Pfeiffer, K.W. West, "Soft spin wave near nu=1: Evidence for a magnetic instability in skyrmion systems", Physical Review Letters, p. , 086806, vol. 100, (2008). Published,

Y. Gallais, A. Pinczuk, L.N. Pfeiffer, K.W. West,, "Inelastic light scattering measurements of spin excitations in Skyrmion systems", Physica E, p. 999, vol. 40, (2008). Published,

B. Karmakar, S. Luin, V. Pellegrini, A. Pinczuk, B.S. Dennis, L.N. Pfeiffer, K.W. West, "Signatures of composite-fermion metals in electron bilayers at nu=1", Physica E, p. 1312, vol. 40, (2008). Published,

S. Kalliakos, C.P. Garcia, V. Pellegrini, A. Pinczuk, B.S. Dennis, L.N. Pfeiffer, K.W. West, M. Rontani, G. Goldoni, E. Molinari, "Correlated states and spin transitions in nanofabricated AlGaAs/GaAs few-electron quantum dots probed by inelastic light scattering", Physica E, p. 1867, vol. 40, (2008). Published,

S. Kalliakos, M. Rontani, C.P. Garcia, V. Pellegrini, A. Pinczuk, G. Goldoni, E. Molinari, L.N. Pfeiffer, K.W. West, "A molecular state of correlated electrons in a quantum dot", Nature Physics, p. 467, vol. 4, (2008). Published,

J. Yan, E.A. Henriksen, P. Kim, and A. Pinczuk, "Observation of anomalous phonon softening in bilayer graphene", Physical Review Letters, p. 136804, vol. 101, (2008). Published,

B. Karmakar, V. Pellegrini, A. Pinczuk, L.N. Pfeiffer, K.W. West, "First-order quantum phase transition of excitons in quantum Hall bilayers", Physical Review Letters, p. 036802, vol. 102, (2009). Published,

A. Singha, V. Pellegrini, S. Kalliakos, B. Karmakar, A. Pinczuk, L.N. Pfeiffer, K. W. West, "Optical anisotropy of electronic excitations in elliptical quantum dots", Applied Physics Letters, p. 073114, vol. 94, (2009). Published,

, P. Plochocka, J. M. Schneider, D. K. Maude, M. Potemski, M. Rappaport, V. Umansky, I. Bar-Joseph, J. G. Groshaus, Y. Gallais, A. Pinczuk, "Optical absorption to probe the quantum Hall ferromagnet at filling factor nu=1", Physical Review Letters, p. 126806, vol. 102, (2009). Published,

Books or Other One-time Publications

Web/Internet Site

Other Specific Products

Product Type:

conference presentation

Product Description:

Invited Conference Presentations:

Yann Gallais, Soft spin waves and magnetic instability in Skyrmion systems, March Meeting of the American Physical Society, New Orleans, LA, March 10-14, 2008.

Aron Pinczuk, Low-lying excitations in quantum Hall systems, Conf. on Quantum Phases and Excitations, Dresden, Germany, June 16-21, 2008.

Vittorio Pellegrini, Correlation-driven first-order quantum phase transition in quantum Hall bilayers 18th Conf. on High Magnetic Fields in Semiconductors, Sao Pedro, SP, Brazil, August 3-8, 2008.

Aron Pinczuk, Quantum Hall systems: new insights from optics, 22nd Condensed Matter Conf. of European Physical Society, Rome, Italy, August 25-29, 2008.

Aron Pinczuk, Raman scattering by electrons in semiconductor quantum Structures, Fall Meeting of European-Materials Research Society, Warsaw, Poland, September 15-19, 2008.

Aron Pinczuk, Spectroscopy of electrons in low-dimensional quantum structures (3 lectures), INFM School on Physics in Low dimensions, Lucca, Italy, October 11-18, 2008.

Aron Pinczuk, Optics in 2D electron systems Workshop on Emergent Nanoscience, Columbia University, December 4-5, 2008.

Vittorio Pellegrini, Optics in quantum dots, Workshop on Emergent Nanoscience, Columbia University, December 4-5, 2008.

Aron Pinczuk, 39th Winter Conf. on Physics of Quantum Electronics, Snowbird, UT, January 4-8, 2009.

Contributed Conference Presentations:

The results from the projects have given rise to numerous contributed presentations at national and international conferences by participants of the program.

Sharing Information:
not applicable

Contributions

Contributions within Discipline:
See attachment

Contributions to Other Disciplines:
None at this time.

Contributions to Human Resource Development:
See segment on Research Training above

Contributions to Resources for Research and Education:
See attachment.

Contributions Beyond Science and Engineering:
See attachment

Conference Proceedings

Categories for which nothing is reported:

Organizational Partners
Any Book
Any Web/Internet Site
Any Conference

Contributions within Discipline

The contributions reported below are from the Pinczuk group and his collaborators. The results from the Stormer group were described in the report filed in February 2008.

The reported work explores striking quantum phases that emerge in high quality low dimensional electron systems. Advanced inelastic light scattering experiments enable the access to physics of fundamental interactions by measurements of low-lying excitations. This research offers novel insights that emanate from unique experimental venues to explore key interactions in emergent quantum phases of electrons in semiconductor structures.

Quantum phases of electrons in higher Landau levels

Electrons in higher Landau levels (Landau level index $N \geq 1$) condense into highly correlated quantum phases. There is a complex interplay between competing quantum states that is dictated by magnetic field, areal electron density and temperature. Of great current interest are emergent phases in the partially populated first excited ($N=1$) Landau level. These states are far less understood than those in the ground ($N=0$) Landau.
Results reported here demonstrate that inelastic light scattering methods provide access to physics of interactions in the $N=1$ Landau level by measurement of low-lying excitation modes.

(a) Characterization of high quality quantum structures

Our projects require that we identify a class of high quality GaAs quantum structures that are suitable for studies of quantum phases of electrons in the partially populated $N=1$ Landau level. These structures need to have relatively high electron areal density $n \geq 2 \times 10^{11} cm^{-2}$, and state-of-the-art high electron mobility $\mu \sim 2 \times 10^{7} cm^{2}/V.sec$. In optics work we have the additional requirement that the 2D electron system need to be stable under the conditions of weak CW illumination.

The results reported below are obtained in one of such structures. Surprisingly, in this sample, as well as in other specimens of this quantum structure family, we find evidence of donor impurities in the GaAs quantum well that is the host of the 2D electron system. Figure 1 displays a signature of the negatively ionized donor center known as D^-. The D^- center consists of a donor that has captured an additional electron from the 2D electron system.

These are unexpected findings for quantum well structures that have ultra-high electron mobility and that display remarkable electron quantum fluids. We note, however, that our collaborators in Russia have identified the D^- center in comparable high quality GaAs quantum structures grown by groups at the Weizmann Institute (Israel) and at the University of Regensburg (Germany).

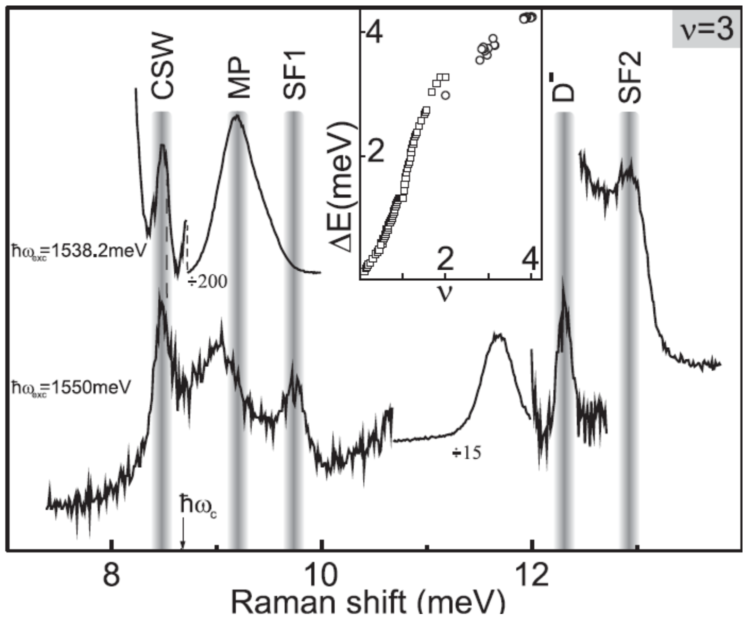

Figure1. *Inelastic light scattering spectra of inter Landau level excitations measured at* ν*=3. These results were obtained at Columbia by A.B. Vankov, a visiting student from the group of I. V. Kukushkin. Spectra at two different incident photon energies are displayed and several transitions are shown. The dependence of spectral intensities on incident photon energy is typical of resonant light scattering experiments. The grey broad vertical lines identify inelastic light scattering peaks. The other features are interpreted as luminescence. CSW and MP are modes in the charge degree of freedom (magneto-plasma waves). SF1 and SF2 are modes in the spin degree of freedom (spin-flip modes). A vertical arrow marks the position of the cyclotron energy at* $\hbar\omega_c$*. Of interest here is the peak labeled* D^- *that represents a transition at the site of a negatively ionized donor within the single GaAs quantum well that hosts the 2D electron system. The donor is believed to be a Si atom from the modulation doping that drifts into the GaAs quantum well. The inset represents the blue shift from* $\hbar\omega_c$ *of the* D^- *transition as function of filling factor (the results in the range* $4\geq\nu\geq2$ *were obtained at Columbia).*

The implication of such results is that there is still plenty of room to great improvements in sample quality by better of control of impurities. Among our goals is the design of molecular-beam-epitaxy (MBE) protocols that minimize the incorporation of impurities in the active GaAs quantum well. We are pursuing these efforts in collaboration with the group of Prof. Loren Pfeiffer (now at Princeton University).

To address this issue in an effective manner we seek signatures of ionized donors in optical spectra measured without magnetic field. The achievement of this goal would enable quick and effective feedback for the MBE growth. These efforts could eventually lead to fabrication of superior quality quantum structures for further advances in the elucidation of physics of intriguing quantum phases in 2D electron systems.

<u>(b) Low-lying excitation modes in the filling factor range 3≥ν≥2</u>

In the initial work we obtain spectra of long wavelength spin wave modes to monitor the state of spin polarization of the electrons that populate the N=1 Landau level. This spin wave mode is pegged at the Zeeman energy E_Z by the requirements of the Larmor theorem.

The states of spin polarization of quantum phases are of great current interest in studies of higher Landau levels. Theoretical evaluations at filling factor ν=5/2 indicate that the lowest energy states have full spin polarization. While it has been universally assumed that the experimentally accessible states in the N=1 Landau level have full spin polarization, this has not been fully tested in experiment.

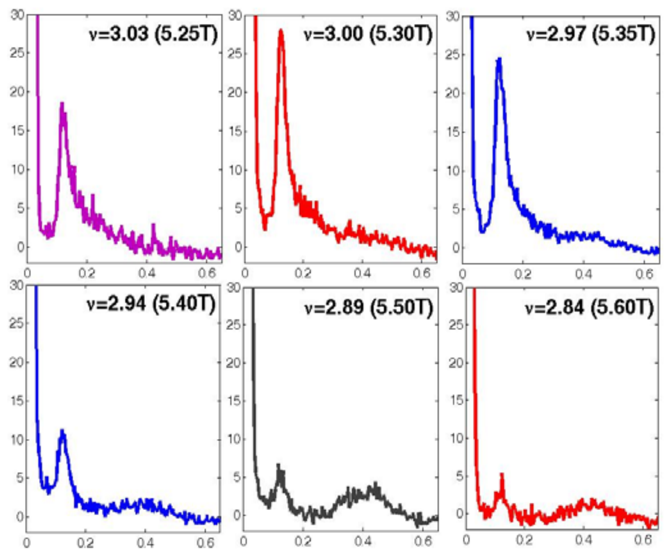

Figure 2: *Filling factor dependence of inelastic light scattering spectra of low-lying excitations in the vicinity of ν=3. The sharp peak is the long wavelength spin wave mode at the Zeeman energy E_Z. At filling factors very close to ν=3 the spectral asymmetry is assigned to breakdown of wave vector conservation that activates larger wave vector modes (this is caused by some loss of translation symmetry due to residual disorder in high quality GaAs structures). The higher energy 'band' at 0.4meV that emerges for ν<2.97 has not been assigned yet. The measurements are done in a dilution refrigerator with cold finger temperature at 43mK.*

The results in Fig.2 show spectra of low-lying spin wave excitations at filling factors near ν=3. There is a marked decrease in the intensity of the mode as the filling factor slightly departs from ν=3. This is a remarkable behavior that could be linked to a loss of spin polarization.

This interpretation is, in fact, supported by results obtained near filling ν=8/3 and near filling factor ν=5/2 that are still being analyzed.

A picture that is forming from the analysis of current results is that as soon as the filling factor is decreased below ν=3 new fermion quasiparticles, composite fermions, enter the picture with a structure of Landau levels that favors spin unpolarized states.

First-order quantum phase transition in quantum Hall bilayers at ν_T=1

We demonstrated a quantum phase transformation between compressible, metallic, and incompressible, excitonic, states in coupled electron bilayers. It occurs in GaAs double quantum wells at total Landau level filling factor ν_T=1. The compressible phase consists of two largely uncoupled composite fermion metals. The incompressible phase has two layers that are strongly coupled in a highly correlated state that supports an exciton density smaller than the free electron density. While the transformation is triggered by tuning the collapse of the tunneling gap Δ_{SAS}, the transition becomes discontinuous (first-order) by impacts of different terms of the electron-electron interactions that prevail on weak residual disorder.

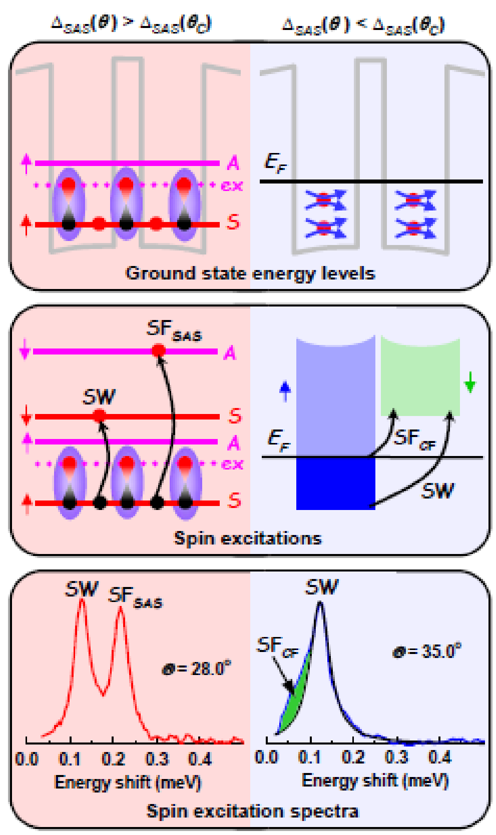

Figure 3: *<u>Upper panel</u>: Schematic of the correlated phases in double layers at ν_T=1. The excitonic quantum Hall phase is on the left. Electron-hole pairs occur between nsymmetric (S) and anti-symmetric (A) spin-up Landau levels. The composite fermion (CF) phase is shown on the right. The Fermi energy indicates the occupied CF levels. <u>Middle panel</u>: energy level diagram and spin excitations in the two phases. SW and SF_{SAS} refer to spin-wave across the Zeeman gap and spin-flip mode across the tunneling gap, respectively. In the CF phase, a spin flip SF_{CF} continuum of collective excitations extends from the Zeeman gap down to an energy value determined by the relative position of the Fermi level within the spin-up and spin-down CF states. <u>Lower panel</u>: Representative spin excitation spectra after background subtraction due to magneto-luminescence and stray light in the two phases at T = 50mK. A lorentzian fit to the SW in the CF phase (black line) highlights the impact of the SF_{CF} continuum (shaded in green).*

The evidence is based on precise determinations of the tunneling gap of the excitonic phase, $\Delta_{SAS}(\theta)$, by inelastic light scattering measurements of low-lying spin excitations. The tilt angle between the layers and the magnetic field is changed in order to control the collapse of $\Delta_{SAS}(\theta)$ and the quantum phase transition. As illustrated in Fig. 3, $\Delta_{SAS}(\theta)$ is the difference between the energies of SF_{SAS} and SW modes.

While there is marked softening of $\Delta_{SAS}(\theta)$ near the critical angle θ_C we observe discontinuous changes in the order-parameter and mode intensity that identify the phase transitions as of first-order.

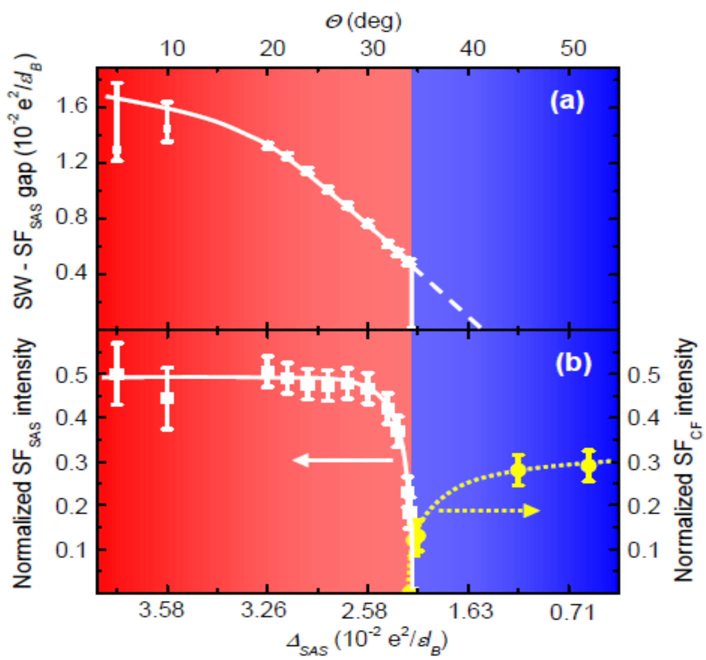

Figure 4: *(a) evolution of the correlated gap of the excitonic phase, i.e. the energy splitting of SW and SF_{SAS} excitations, as afunction of tunnelling gap or tilt angle between the layers and the magnetic field. The splitting remains finite at the phase boundary between the excitonic phase (red shaded) and the composite fermion metal (blue shaded). (b) plot of integrated spin-flip excitation mode intensity. Data correspond to the intensities of SF_{SAS} (white) and SF_{CF} (yellow) modes (solid and dotted lines are guide for the eyes). The values are obtained after normalization with respect to the spin-wave SW intensity to take into account the angular dependence of oscillator strength of spin excitations.*

There is great current interest in the quantum phases transitions in electron bilayers in the quantum Hall state at total filling factor ν_T=1. The results reported above and work in progress shows that spectroscopy methods provide novel insights.

Contributions to other disciplines

None at this time.

Contributions to Education and Human Resources

See segment on Research Training above.

Contributions to Resources for Science and Technology

As in previous years, we maintain that the most important resources we are creating are our well trained graduate students and post-docs. Beyond this, Stormer and his postdocs are pioneering processing techniques for graphene suspension and ultra-sensitive far-infrared techniques in very high magnetic fields. We firmly believe that suspended graphene will become THE material of choice for future investigations into graphene. The far-infrared system we have substantially modified for graphene research has already become a standard tool for visitors to the NHMFL magnet lab. Pinczuk is pioneering schemes for optical experiments on low-dimensional electrons at very low temperatures that will have impact on a broader set of future experiments than just his own or just among his research colleagues. In fact the system he developed is currently being reproduced in other institutions.

Contributions Beyond Science and Engineering

Our research work is largely of a fundamental nature and its results predominantly contribute to science. However, particular in our graphene research we are also laying the ground work for the evaluation of a new material that is considered as a material for future electronic systems. In addition, we maintain that the fundamental insights we achieve also contribute in a broader sense to society. This is very much our experience from discussions and feedback we are getting from the audience after giving talks to the general public. There is a very high level of interest in the weirdness of quantum mechanics among the less initiated and our research results and our presentations contribute to addressing this interest.

Animal, Human Subjects, Biohazards

To the best of our knowledge, there are no such hazards in our experiments.

Contributions to Education and Human Resources

See segment on Research Training in this report.

Contributions to Resources for Science and Technology

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