Circularly polarized resonant Rayleigh scattering and Skyrmions in the $\nu = 1$ quantum Hall ferromagnet

V. Bellani,[1] F. Rossella,[1] M. Amado,[2,3] E. Diez,[3] K. Kowalik,[4,*] G. Biasiol,[5] and L. Sorba[6]

[1]*Dipartimento di Fisica "A. Volta" and CNISM, Università degli Studi di Pavia, 27100 Pavia, Italy*
[2]*GISC, Departamento de Física de Materiales, Universidad Complutense, 28040 Madrid, Spain*
[3]*Laboratorio de Bajas Temperaturas, Universidad de Salamanca, 37008 Salamanca, Spain*
[4]*Laboratoire National des Champs Magnétiques Intenses, 38042 Grenoble, France*
[5]*Istituto Officina dei Materiali CNR-TASC, 34012 Trieste, Italy*
[6]*NEST, Istituto Nanoscienze-CNR and Scuola Normale Superiore, 56126 Pisa, Italy*

We use the circularly polarized resonant Rayleigh scattering (RRS) to study the quantum Hall ferromagnet at $\nu = 1$. At this filling factor, we observe a right-handed copolarized RRS which probes the Skyrmion spin texture of the electrons in the photoexcited ground states. The resonant scattering is not present in the left-handed copolarization, and this can be related to the correlation between Skymionic effects, screening, and spin wave excitations. These results evidence that RRS is a valid method for the study of the spin texture of the quantum Hall states.

PACS number(s): 73.43.Lp, 73.20.Mf, 78.35.+c

The interaction between electrons in the quantum Hall regime gives rise to collective ground states. At filling factor $\nu = 1$, the two-dimensional electron system turns into an itinerant ferromagnet while moving away from this filling factor, the system depolarizes rapidly due to the formation of a spin texture called Skyrmion.

The Skyrmions have been originally observed using optically pumped nuclear magnetic resonance by Barret *et al.*[1] Successively the depolarization of the ferromagnet very close to $\nu = 1$ and the related spin texture have been studied mainly by means of interband optical absorption[2–4] and inelastic light scattering.[5] The temperature affects the ferromagnetic order, and at temperatures larger than the Zeeman gap, the formation of low energy spin excitons separates the ferromagnet from clusters. However, the lateral confinement of these clusters pushes the energies of the spin excitons up, thus preserving the ferromagnetic order locally.[6] Indeed, the Skyrmion texture can be observed in optical absorption experiments at liquid helium temperature[2,3,18] up to several Kelvin.[2,3]

In this Brief Report, we evidence the Skyrmion spin texture at $\nu = 1$ by means of an elastic resonant Rayleigh scattering (RRS), in a one-side modulation-doped GaAs-AlGaAs quantum well. In this experiment, the incident light is resonant with the photoluminescence (PL) from the recombination between the two-dimensional electron gas (2DEG) electrons and the photogenerated holes. The selection of the circular polarization of the incident and scattered light allows to probe the different Zeeman split sublevels. Close to $\nu = 1$, we observe a right-handed copolarized RRS with the Skyrmion spin texture, while the left-handed copolarized spectra does not present such RRS, a behavior that can be related to the correlation between the Skyrmion, screening, and spin waves.[7,8]

RRS proved to be a valid tool to study the quantum mechanics of the electrons and the dephasing process in low dimensional systems,[9] and has been used to study the quantum Hall phases in a double coupled 2DEG (Ref. 10) in order to investigate the formation of a nonuniform electron fluid

close to the phase transition toward the compressible state. The light emission from the 2DEG, excited with a laser radiation resonant to the transition energy of the exciton, comprises a contribution which maintains its coherence with the excitation and one which does not. The former is the RRS which depends on eigenenergies and wave-function properties including the spin, while the latter is the (incoherent) luminescence.[11,12]

The experiment was performed on a 20-nm-thick one-side modulation-doped GaAs-AlGaAs single quantum well with carrier density $n = 1.8 \times 10^{11}$ cm^{-2} and mobility $\mu = 1.6 \times 10^6$ cm^{-2} V^{-1} s^{-1} measured at 1.4 K. Recent studies show that in 2DEG with intermediate electron density of about 10^{11} cm^{-2} and mobility between 1×10^6 and 3×10^6 cm^{-2} V^{-1} s^{-1}, the interplay between disorder and Coulomb interactions can reveal interesting interaction-related effects such as energetic anomalies of the charged excitons[13] and peculiar fractional states such as the $\nu = 3/8$[14]. The optical experiments were realized using a Ti-sapphire laser with the sample mounted in a cryostat with liquid ^{4}He under pumping with the magnetic field generated by a resistive magnet. The light was sent and collected through two optical fibers, and was circularly polarized using linear polarizers coupled to quarter wave plates placed in the optical paths between the fibers and the sample. In the following, we will use the notation $\sigma^{\pm}\sigma^{\pm}$ to identify the polarization, indicating in successive order the polarization of the excitation and of the detection. The measurements were performed in Faraday configuration with nearly backscattering geometry, being the angle of incidence and collection of only a few degrees.

Figure 1 shows the energy of the PL peaks as a function of the magnetic field (B). Several transitions can be observed due to recombination of the excitons formed by photogenerated holes and electrons of the 2DEG merged with the photogenerated electrons. The labels L_0, L_1, and L_2 identify the transition between electrons and holes in their first, second, and third Landau level (LL), respectively. We can see that at 4.1 T, the transitions from the second electron LL, i.e., L_1, disappear. This is due to the emptying of this LL which takes place for
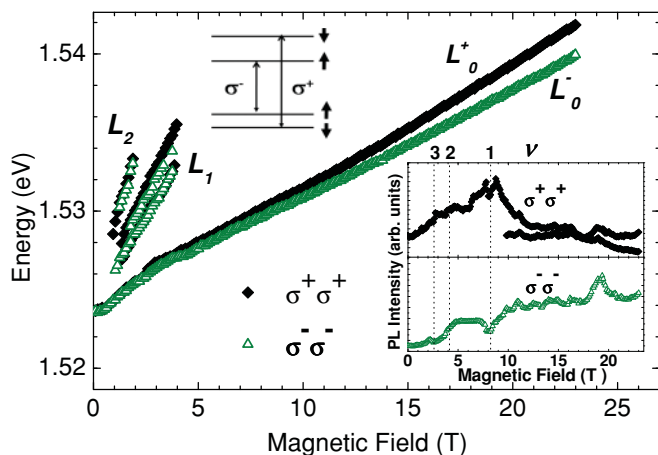
FIG. 1. (Color online) Energy of the PL transitions as a function of the magnetic field at temperature of $\sim$1.4 K. In the inset, the intensity of the PL peaks is reported. The schematic view of the spin split level, L_0, is also reported.

$\nu > 2$ since the Fermi level drops to the first LL, and allows us to identify the position of $\nu = 2$.

The lower energy transition observed in the two copolarized spectra comes from electrons in the Zeeman split lower lying LLs, namely, L_0^- (lying at the lower energy, for transition between $+1/2$ spin electrons and $-3/2$ spin holes) and L_0^+ (lying at higher energy, due to transitions between $-1/2$ spin electrons and $+3/2$ spin holes). In the insets of Fig. 1, we show the PL intensity as a function of B for the $\sigma^+\sigma^+$ and $\sigma^-\sigma^-$ copolarized spectra. The PL intensity has a clear reduction at $\nu = 1$ (at $B = 8.2$ T) for both $\sigma^+\sigma^+$ and $\sigma^-\sigma^-$ polarizations. This behavior is attributed to a strong inhibition of the radiative recombination related to localization and changes in the screening response of the electron gas, which leads to reduced electron-hole overlap and broadening of the density of state.[15,16]

In Fig. 2, we present the RRS response of the quantum Hall ferromagnet around $\nu = 1$. The figure shows the series of spectra of the collected light, which include either the PL and the scattered light, measured at $\nu = 1$ for the two $\sigma^+\sigma^+$ (a) and $\sigma^-\sigma^-$ (b) polarizations. These spectra were recorded with a charge coupled device (CCD) detector, scanning continuously the energy of the laser light in the energy range of the L_0^+ and L_0^- levels. We can observe that the $\sigma^+\sigma^+$ polarized spectra show a clear RRS at the same energy of the PL emission from L_0^+. However, the $\sigma^-\sigma^-$ spectra do not show any RRS, and we also found that the measurements taken with cross polarizations $\sigma^+\sigma^-$ and $\sigma^-\sigma^+$ do not show any enhancement in the elastic scattering, a behavior that will be explained in the following. We notice that the nonresonant component of Rayleigh scattering is very high, and the extraction of the resonant component against the strong background is a demanding task.

The effect of the Coulomb screening has to be taken into account in order to describe the RRS and the photoexcited ground state close to $\nu = 1$. In the one-side modulation-doped GaAs–AlGaAs quantum wells, the electron and the photogenerated hole usually lie in the opposite sides of the well. When the well width d is greater than the magnetic length
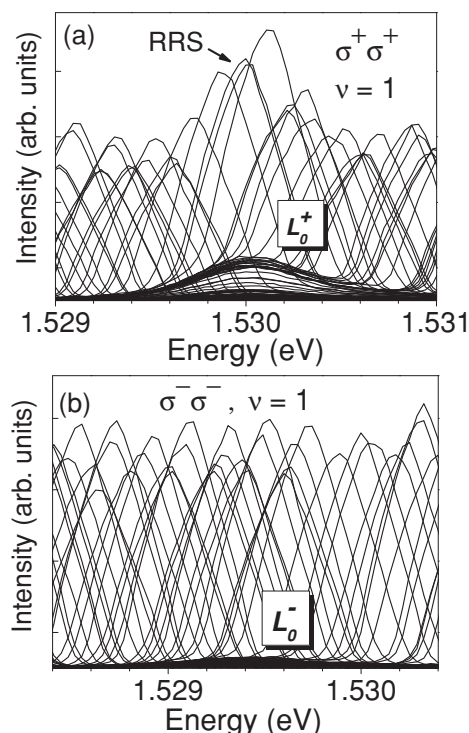

FIG. 2. The light scattering plus emission spectra around $\nu = 1$ for (a) the $\sigma^+\sigma^+$ and (b) $\sigma^-\sigma^-$ polarizations at $T \sim$1.4 K.

l, as in our case since $l \sim 9$ nm at $\nu = 1$, the electron-electron interaction dominates the electron-hole one. Consequently, the electrons form a Skyrmion first which then bounds with the valence hole, forming a state called Skyrmion-hole[8] or Skyrmion exciton[7] and the RRS close to $\nu = 1$ is resonant with the PL arising from the recombination of this state.

In low-dimensional systems, the RRS is the resonant light scattering into all directions and is due to the localized excitonic states.[11,12] In our case around $\nu = 1$, the quantum Hall localization of the Skyrmion excitons adds up to the localization due to the unintentional fluctuations of the quantum well interfaces and to the one due to the finite exciton lifetime and diffusion length. The quantitative evaluation of the RRS observed in our system is complex, the origin of this resonant scattering has been for instance studied using Anderson models[11,12] and solutions of the scattering process have been proposed using low-order Feymann diagrams.[17] The simplest approximation is to assume a RRS polarization proportional to the polarization of the Skyrmion excitons and to consider full polarization at $\nu = 1$ and zero polarization when the RRS is absent. This approximation allows the comparison of the data with the simple Skyrmion model.

The quantum Hall ferromagnet at $\nu = 1$ is described in terms of Skyrmion spin texture, and in the model for independent electrons proposed by Barret *et al.*[1] the spin polarization is $S_z(\nu) = S(\frac{2-\nu}{\nu}) - (S - 1)$ for $\nu > 1$ and $S_z(\nu) = \frac{1}{\nu} - (2A - 1)(\frac{1-\nu}{\nu})$ for $\nu \leqslant 1$, where $S(A)$ is a parameter that gives the number of spin flips per unpaired quantum of flux above (below) $\nu = 1$.

In Fig. 3, we show the value of the normalized RRS scattering, as a function of ν for the four polarization configurations. These values have been taken as a ratio between
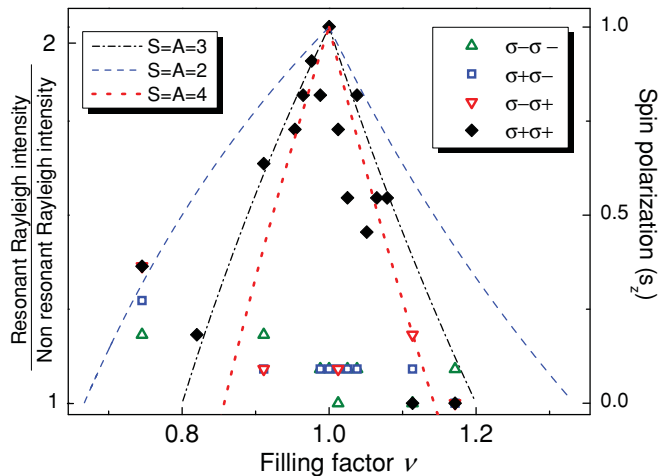
FIG. 3. (Color online) The ratio between the RRS and nonresonant light scattering intensities for the four cross polarizations. The lines refer to the Skyrmion model of Ref. 1 with the different values of the parameter $S = A = 2, 3$, and 4.

the maximum RRS enhancement and the constant Rayleigh scattering intensity out of resonance. Figure 3 reports the Skyrmion model with $S = A = 2, 3$, and 4 considering an equal value of S and A in order to reflect the particle-hole symmetry which requires the size of the Skyrmion to be the same as the anti-Skyrmions.[2] We can see that the values $S = A = 2$ and 3 are the closest to the experimental points, in particular, the value $S = A = 3$ has been found in the past in experiments on GaAs quantum wells with similar widths,[1,2,18] and corresponds to three flipped spins per quantum flux.

The presence of RRS in $\sigma^+\sigma^+$ polarization, and its absence in the $\sigma^-\sigma^-$ can be due to the correlation between Skyrmions, screening, and spin waves. The energy dispersion of the RRS signal around the optical resonance has been shown to be dependent on the energy dispersion of the homogeneous linewidth and of the dephasing times.[11,12] Theoretical calculations of Asano and Ando[7] indicate that

in systems with small finite values of Zeeman splitting, as in the GaAs-AlGaAs heterostructure ($g_e \sim -0.4$), the spin and charge degree of freedom are strongly correlated, and this plays an important role in presence of a photoexcited hole. Indeed, the formation of multiple spin flips aids the hole screening when the electron-electron interaction strength is comparable with the electron-hole one. One of the main results is the presence of a jump in the energy of the σ^- polarized luminescence when ν passes across the value 1, which is absent in σ^+ polarization. Other theoretical models[8] show that at $\nu = 1$ and around, the σ^- luminescence presents secondary emission peaks in the low-energy side of the main emission peak, intensity and energy shift of which are related to the spin wave excitations.[8] The σ^+ emission is instead not modified and is a single-peaked structure. Therefore, dephasing times of the homogeneous linewidth for the σ^- emission would be affected and their energy dispersion could present rapid variation in correspondence of these secondary emissions. As a consequence, the RRS would be consequently reduced, up to be no more resolvable with respect to the nonresonant scattering response.

In summary, we have used the PL spectroscopy to investigate the magneto-excitonic transitions in a high-mobility 2DEG and the RRS to probe the collective spin texture of the quantum Hall ferromagnet at $\nu = 1$. The RRS present in the $\sigma^+\sigma^+$ copolarized measurements reveals the Skyrmion spin texture of the 2DEG electrons in the photoexcited ground state. Instead, the interplay between Skymionic effects, screening, and spin wave excitations results in a modified σ^- polarized emission, and consequently in the absence of RRS in this polarization. These findings indicate that RRS can be used as a valid tool for the study of the spin textures of the quantum Hall systems.

*Present address: Department für Physik, Ludwig Maximilians Universität, 80539 München, Germany.

[1]S. E. Barrett, G. Dabbagh, L. N. Pfeiffer, K. W. West, and R. Tycko, Phys. Rev. Lett. **74**, 5112 (1995).

[2]E. H. Aifer, B. B. Goldberg, and D. A. Broido, Phys. Rev. Lett. **76**, 680 (1996).

[3]M. J. Manfra, E. H. Aifer, B. B. Goldberg, D. A. Broido, L. Pfeiffer, and K. West, Phys. Rev. B **54**, 17327 (1996).

[4]J. G. Groshaus, V. Umansky, H. Shtrikman, Y. Levinson, and I. Bar-Joseph, Phys. Rev. Lett. **93**, 096802 (2004).

[5]A. S. Zhuravlev, A. B. Vankov, L. V. Kulik, I. V. Kukushkin, V. E. Kirpichev, J. H. Smet, K. v. Klitzing, V. Umansky, and W. Wegscheider, Phys. Rev. B **77**, 155404 (2008).

[6]I. K. Drozdov, L. V. Kulik, A. S. Zhuravlev, V. E. Kirpichev, I. V. Kukushkin, S. Schmult, and W. Dietsche, Phys. Rev. Lett. **104**, 136804 (2010).

[7]K. Asano and T. Ando, Solid. State Commun. **127**, 582 (2003).

[8]R. L. Doretto and A. O. Caldeira, Phys. Rev. B **71**, 245330 (2005).

[9]V. Bellani, M. Amado, E. Diez, C. Koerdt, M. Potemski, and R. Hey, Phys. Rev. B **76**, 075349 (2007).

[10]S. Luin, V. Pellegrini, A. Pinczuk, B. S. Dennis, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **97**, 216802 (2006).

[11]R. Zimmermann, and E. Runge, Phys. Rev. B **69**, 155307 (2004).

[12]C. Schüller, K.-B. Broocks, P. Schröter, Ch. Heyn, D. Heitmann, M. Bichler, W. Wegscheider, Tapash Chakraborty, and V. M. Apalkov, in *Quantum Coherence, Correlation and Decoherence in Semiconductor Nanostructures*, edited. by T. Takagahara (Academic Press, London, 2003).

[13]C. Schüller, K. B. Broocks, P. Schroter, C. Heyn, D. Heitmann, M. Bichler, W. Wegscheider, T. Chakraborty, and V. M. Apalkov, Phys. Rev. Lett. **91**, 116403 (2003).

[14]V. Bellani, F. Dionigi, F. Rossella, M. Amado, E. Diez, G. Biasiol, and L. Sorba, Phys. Rev. B **81**, 155316 (2010).

[15]B. B. Goldberg, D. Heiman, A. Pinczuk, L. Pfeiffer, and K. West, Phys. Rev. Lett. **65**, 641 (1990).

[16]M. Dahl, D. Heiman, A. Pinczuk, B. B. Goldberg, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **45**, 6957 (1992).

[17]N. Garro, L. Pugh, R. T. Phillips, V. Drouot, M. Y. Simmons, B. Kardynal, and D. A. Ritchie, Phys. Rev. B **55**, 13752 (1997).

[18]P. Plochocka, J. M. Schneider, D. K. Maude, M. Potemski, M. Rappaport, V. Umansky, I. Bar-Joseph, J. G. Groshaus, Y. Gallais, and A. Pinczuk, Phys. Rev. Lett. **102**, 126806 (2009).