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UNIVERSAL MAGNETO-LUMINESCENCE KINETICS IN THE MAGNETICALLY FROZEN 2D ELECTRON SUSTEM

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Kinetics of recombination of electrons and acceptor-bound holes in AlGaAs-GaAs heterostruture obey the single-exponential decay in the liquid phase of 2D electrons, whereas the localization gives rise to a broad spectrum of recombination rates, especially in the magnetic freeze-out regime. This results in the power-law dependence $I(t) \propto (\tau/t)^{\alpha}$ at the tail of recombination kinetics, which has the *universal* exponent $\alpha = (1-\nu)^{-1}$ at $\nu < 1$ for all samples examined experimentally in this work.

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During the recent years, the localization of 2D electrons at high magnetic fields has been extensively discussed [1]. In pure enough systems, the Coulomb interaction gives rise to the crystallization of electrons into the Wigner solid state [2], nevertheless, a much more common situation is a magnetic freeze-out of 2D carriers in substantially disordered structures. The electron localization in heterostructures at high magnetic fields has been detected in numerous transport experiments [3]. However, for a detailed study of the magnetic freeze-out regime, alternative methods are required, especially regarding the growing interest to the electron-electron correlation in the localized state and, as a consequence, to its short-range structure.

The approach which we use below is based on the analysis of the time-resolved electron-hole recombination in heterostructures [4–7]. This reference is to the experimental situation [5,7] in which a small number of optically generated valence-band holes are tightly bound at acceptors from a diluted δ-doped layer [8] and serve as a local probe (at the length scale of few nanometers) of a system of electrons occupying the lowest size-quantized subband and forming the 2D layer. It is a peculiarity of the recombination process involving acceptor bound hole that the life-time of each hole, τ, is determined by the local density $\rho_e(r_h)$ of the electron wave function at the acceptor position, so that the spectrum of recombination rates reflects the distribution of the local 2D electron density: $\tau^{-1} = \sigma\rho_e(r_h)$ [6] (parameter σ depends on the distance d between the interface and acceptor δ-layer and potential profile of the well).

When 2D electrons form a liquid with microscopically homogeneous density, $\rho_e(r_h) \equiv n_e$, all holes are in equivalent positions and have the same value of recombination rate $\tau_0^{-1} = \sigma n_e$. This results in a single-exponential dependence $I(t) = I_0 \exp(-t/\tau_0)$ of the luminescence intensity as a function of delay time t

after the pulse. When 2D electrons are localized at the short-range distances (shorter than the inter-particle spacing), the life-time of holes takes a broad distribution. Such a situation typically takes place in disordered electron systems at small filling factors $\nu < 1$. In the present Letter, we report a detailed analysis of the time-resolved luminescence in several samples with various levels of disorder and densities which allows us to claim an observation of the universal recombination kinetics in a wide range of filling factor.

The experiment was performed on GaAs-AlGaAs single heterojunctions with a δ-doped monolayer of Be acceptors ($n_A = 1.3 \cdot 10^9\,\mathrm{cm}^{-2}$) located in the wide ($1\mu$m) GaAs buffer layer at a distance d from the interface [8] (in all studied samples d was close to 30 nm). Several samples were examined with different densities (from $n_e = 0.6 \cdot 10^{11}\mathrm{cm}^{-2}$ to $n_e = 1.5 \cdot 10^{11}\mathrm{cm}^{-2}$) and mobilities (from $\mu = 10^4\mathrm{cm}^2/\mathrm{Vs}$ to $\mu = 10^6\mathrm{cm}^2/\mathrm{Vs}$). For photoexcitation, we used pulse from a tunable Ti-Sapphire laser (wavelength $\sim$ 800 nm) with a variable duration from 20 ns to 10 μs, peak power of $10^{-5} - 10^{-4}\mathrm{W/cm}^2$ and frequency of 10^7-10^3Hz. The luminescence spectra were detected by a gated photon counting system. The samples were mounted in the mixing chamber of a He^3/He^4 dilution refrigerator. We control the temperature of 2D electrons and the time dependence of their density n_e by monitoring optical analog of Shubnikov - de Haas oscillations [9].

Fig.1 shows the raw data of typical recombination kinetics measured for one of the samples in different magnetic fields. The common feature of the recombination kinetics observed in all the samples at the filling factor $\nu = 1$ and slightly above it is a purely exponential decay of the magneto-luminescence intensity, $I(t) \propto \exp(-t/\tau_0)$. This manifests the homogeneity of the electron density at $\nu = 1$, which is a well known property of many-body wave-function corresponding to a completely filled Landau level [10] and shows that the disorder is not strong enough to take over electron-electron correlations at $\nu = 1$ and to mix different Landau levels with opposite spins. This is an important feature of the class of the systems studied in this Letter, since it means that, despite of disorder, we always study the properties of electrons filling only the lowest Landau level without any inter-Landau-level mixing.

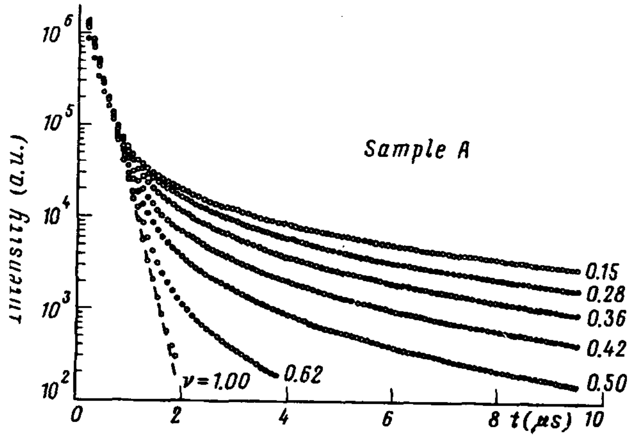
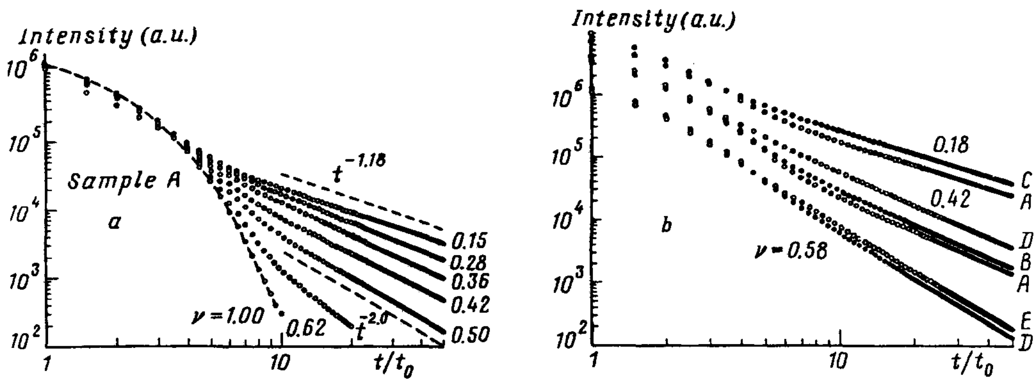
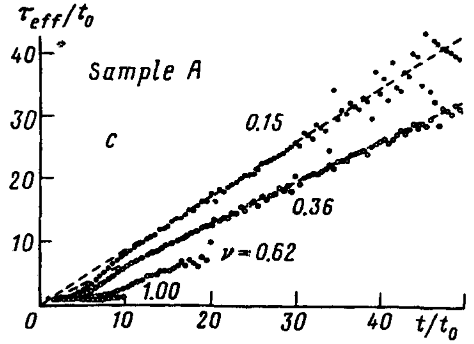


Fig.1. Raw data of the magneto-luminescence kinetics, measured in different magnetic fields for sample A. Numbers indicate the value of the filling factor

In contrast to such a purely 'liquid-type' behavior, the recombination kinetics at smaller filling factors is characterized by a recombination slowed down at the tails. The latter appears, first, at filling factors relatively close to 1 and, then,





Parameters of samples studied in this work

Sample	Density, n_e ($\times 10^{11}$ cm^{-2})	Mobility ($\times 10^5$cm^2/Vs)	τ_0 ($\times 10^{-7}$s)
A	0.60	3.85	1.9
B	0.80	0.94	2.3
C	0.71	0.43	2.2
D	0.60	0.21	2.0
E	1.43	0.11	2.9

Fig.2. Representation of the magnetoluminescence kinetics, measured for several samples and various filling factors. *a*) log-log plot of the same data as in Fig.1. Dashed lines show the examples of an asymptotical fit using the power law dependence. *b*) Comparison of the magnetoluminescence kinetics measured in different samples for close values of the filling factor. The groups of curves corresponding to the same value of ν are arbitrarily shifted along the vertical axis. Parameters of all the samples are enlisted in Table. *c*) Effective (instant) recombination time vs. delay time measured for sample *A*

develops into a long-living recombination with a pronounced power-law temporal dependence (see Fig.1 and Fig.2a). These deviations of $I(t)$ from a single-exponential behavior indicate the formation of mesoscopic-scale inhomogeneities in the electronic system (at the length scale of the order of $n_e^{-1/2}$). To analyze comprehensively the long-living recombination tails from the disordered electron gas, especially in the magnetic freeze-out regime, we compare the kinetics measured in several samples with various electron densities and the level of disorder. The earlier theory [5,6] predicts these tails to have the power-law form at the long-time delay,

$$I(t) = I_0 \left(\frac{\tau_0}{t}\right)^{\alpha}, \qquad (1)$$

with the exponent α which can be approximated by $\alpha \approx 1 + \nu$ at small filling factors (some kind of a gas approximation in which only the contribution to the total local density from the closest localized single-electron state is taken into account).

Fig.2a shows that the estimation in Eq. (1) reasonably describes the long-delay tails of magneto-luminescence kinetics at small ν's. On the other hand, the power-law kinetics also persists at higher values of a filling factor, up to $\nu \approx 0.85$. This behavior is definitely related to disorder, since the power-law tails are more pronounced in samples with lower mobilities, what is illustrated by Fig.2b where we compare the form of $I(t)$ measured in very different samples. In contrast to that, the spectrum of possible exponents α is insensitive to the number of defects or electron density in the structure: In all samples we studied, these exponents are the same for the same values of the filling factor.

To make a quantitative analysis, we determine the values of the exponent α from the raw data in two ways. First, we make a linear asymptotical fit of the plot presenting $\ln(I(t))$ vs. $\ln t$, as shown in Fig.2a,b. Another way [5] is to analyze an instant value of the recombination time $\tau_{eff} = [-d\ln(I)/dt]^{-1}$ (shown in Fig.2c), which obeys a linear dependence $\tau_{eff}(t) = t/\alpha$ in the case when the regime of Eq.(1) is realized. Both of these two procedures give pretty similar results, and the full spectrum of exponents obtained from working out the data measured for different samples is represented in Fig.3 (here, we plot the value of α^{-1} instead of α).

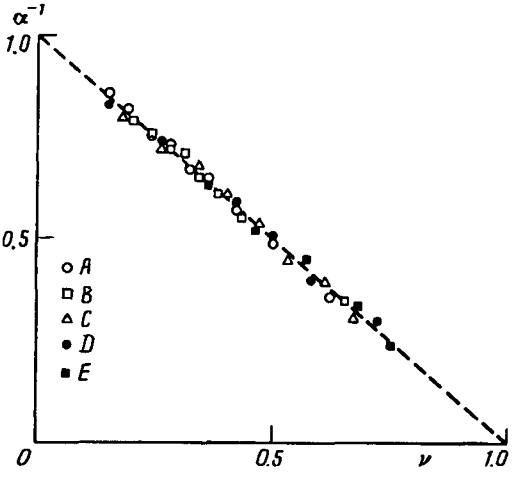


Fig.3. The spectrum of exponents α found in different samples with different mobilities and electron densities plotted versus the filling factor. All the exponents group close to the universal dependence $\alpha = (1-\nu)^{-1}$

A striking feature of the result represented in Fig.3 is that all the values of the exponent α we were able to find in structures with various densities and very different level of disorder group around a single filling-factor-dependent function which can be interpolated by

$$\alpha = (1-\nu)^{-1}. \tag{2}$$

Although in the limit of small filling factors, $\nu \ll 1$, this is in a good agreement with an estimation $\alpha \approx 1+\nu$ which we discussed earlier [5,6], we have no rigorous microscopic explanation of an empiric dependence in Eq.(2) in the full range of filling factors where it was found. However, by treating the recombination rate of each individual acceptor-bound hole as a measure of the local 2D electron density, the power-law long-living tails in the recombination kinetics indicate the existence of power law asymptotics

$$f(w) \propto w^{\beta}, \quad \alpha = \beta + 2, \tag{3}$$

of the distribution function of local electron density $\rho_e(r_h)$ in the limit of $w = 2\pi\lambda_H^2\rho_e(r_h) \ll 1$. Being formed by electrons from the lowest Landau level only - the property which we suggest from the behavior of a system at $\nu = 1$, - the local electron density is limited by $\rho_e(r_h) = (2\pi\lambda_H^2)^{-1}$. It is amusing to note that would Eq.(3) describe the distribution of local densities in the entire region of $0 < w < 1$ where the latter is defined, the only possible value of the exponent β that answers the criterion of normalization of the function f and gives a correct value of the sheet electron density, $\int_0^1 wf(w)dw = \nu$, is $\beta = (2\nu - 1)/(1 - \nu)$ which exactly corresponds to the observed dependence $\alpha = 2 + \beta = 1/(1 - \nu)$.

Of course, we cannot give a full credit to the form of the distribution of the local density as a whole suggested in such a free manner: We have only an experimental evidence of a power-law asymptotics on the low-density side of $f(n_e)$. However, the result of Eq.(3) is interesting as an asymptotic limit, since it manifests the behavior of local electron density near the localized nodes ($\Psi = 0$) of the many-body electronic wave function at the lowest Landau level at $\nu < 1$. In particular, if an analytic form of the density near a node r_0 was assumed, $\rho_e(r - r_0) \propto (r - r_0)^\gamma$, the result of the present work immediately gives the index $\gamma = 2(\nu^{-1} - 1)$.

In conclusion, we observe the power-law magneto-luminescence kinetics at the long delay, $I(t) \propto (\tau_0/t)^\alpha$, with the spectrum of exponents $\alpha(\nu)$ which has a universal behavior $\alpha = 1/(1 - \nu)$ in a wide range of filling factors $(0.15 < \nu < 0.85)$ and in a broad variety of samples. We interpret this result in terms of power-law statistics of distribution of local electron density at small values $2\pi\lambda_H^2 n_e(r_h) \ll 1$. Since the universal kinetics of magneto-luminescence indicates the presence of localized states, we believe that it can be used for testing the evolution of the system when approaching the metal-insulator transition point.

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