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Research Article

Bunching and Antibunching of Quasiparticles in the Fractional Quantum Hall Effect

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Abstract

The transformation of a two-dimensional electron gas in a semiconductor into a quasiparticle gas at low temperature in a strong magnetic field is considered using the quantum fractional Hall effect. Statistical interference effects—bunching and antibunching of quasiparticles—are studied. The dispersion of the number of quasiparticles in a single state and the correlation between the number of quasiparticles in subsystems are detected, and the quasiparticle bunching coefficient is investigated. The correlation increases with decreasing Landau level filling factor, which is determined by the electron concentration. As the filling factor decreases, the bunching coefficient increases at quasiparticle energies exceeding the chemical potential of the gas. When the Landau level filling factor changes from one to zero, the quasiparticles transform from initial fermions (electrons), obeying the Pauli principle, to bosons, which experience mutual interference attraction and maximum bunching. According to the fractional quantum Hall effect, the Landau level filling factor determines the effective charge of a quasiparticle and the effective magnitude of the external magnetic field. In the bosonic state, a gas of quasiparticles has zero effective charge, zero effective external magnetic field and maximum bunching. Therefore, an external electromagnetic field has no effect on the quasiparticle levels, with the exception of the ground state, and does not cause transitions between them in the form of emission, absorption, or reflection of light. Applied to the electron model of the Universe, it can be assumed that Dark Matter is a gas of Hall quasiparticles formed by ordinary electrons in the bosonic state at ultra-low temperatures. The electron model of the Universe can be studied experimentally.

Keywords

Quasiparticles, Dispersion, Correlation, Bunching, Antibunching, Dark Matter, Big Bang

1. Introduction

The statistical properties of a quasiparticle gas follow from the definition of dispersion, or the standard deviation from the mean number of quasiparticles $D = \overline{(\Delta n)^2}$. The expression for dispersion is derived from the energy distribution of the mean number of quasiparticles. The correlation of the particle numbers is found by mentally dividing the system into two subsystems and substituting the results into formulas for determining and expressing dispersion. The statistical behavior of a quasiparticle gas is described using the bunching coefficient, which is the correlation between the deviations from the mean number of quasiparticles in the subsystems, averaged over the mean values of the quasiparticle numbers

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$N_b \equiv \frac{\overline{\Delta n_1 \Delta n_2}}{\bar{n}_1 \bar{n}_2}$ [4]. The result does not depend on the method of dividing the quasiparticle system into subsystems and has a domain of definition from fermions to bosons $-1 \le N_b \le 1$.

2. The Fractional Quantum Hall Effect

A semiconductor layer of area S is perpendicular to a uniform magnetic field $B \approx 13$ T. The electron mean free path is large, the semiconductor thickness is much smaller than the magnetic length $l_M = \sqrt{\hbar/(eB)} \approx 10$ nm, and the electron gas is two-dimensional. Electrons at the Landau level differ in the positions of the center of cyclotron motion with a state degeneracy factor of $N_\Lambda = eBS/h$. In the fractional Hall effect with a surface electron density of N_e, the electrons are located at the lower level with a filling factor (the population factor of the Landau level)

$$\nu \equiv \frac{N_e}{N_\Lambda \bar{n}} = \frac{hn_S}{eB\bar{n}} \cong \frac{hn_S}{eB}, \qquad (1)$$

where $\bar{n}$ is the average population of the state by particles. For an electron gas $\bar{n} = 1$ at $\varepsilon < \mu$, where μ is the chemical potential of the gas. At a gas temperature of $T \approx 30$ mK, the distance between adjacent levels is large $\hbar\omega_c = \hbar eB/m >> kT$, and thermal transitions of microparticles do not occur. The external magnetic field is formed by a ring current of electrons, coherent at low temperature. To reduce the energy, the gas weakens the external magnetic field, attaching magnetic fluxes with vortices of the wave function phase to the electrons, and the electrons turn into quasiparticles. The vortex carries a quantum of magnetic flux $\Phi_1 = h/e$. By selecting n_S and B, we obtain Abelian quasiparticles with the Laughlin filling factor $\nu = 1/(2p+1)$, where the parameter $p = 1, 2, \ldots$. Each electron captures $2p$ vortices, the quasiparticle receives a magnetic flux $2p\Phi_1$, and the external field B is weakened to an effective value

$$B^* = B - 2p\Phi_1 n_S = B(1-2p\nu) = \frac{B}{2p+1} = \nu B. \qquad (2)$$

Capture of a part of the external field means the consistency of the quasiparticle with external charges creating a magnetic field. If the external field is created by negative charges, then they move in the opposite direction compared to the cyclotron movement of the electron, partially screening its charge. For a "dressed" electron, the effective charge modulus $e^* \le e$ is a consequence of Landau diamagnetism. Quasiparticles are placed in a weakened external magnetic field, and the filling factor increases to its maximum value $\nu^* = \frac{hn_S}{e^* B^* \bar{n}} = 1$ at low temperatures. The fractional Hall effect for electrons transforms into the integer Hall effect for quasiparticles. The concentration of quasiparticles is equal to the concentration of the original electrons, according to the conservation law of lepton charge. From this $n_S = \nu \frac{eB}{h} = \frac{e^* B^* \bar{n}}{h}$ we find $\frac{e^*}{e}\frac{B^*}{B}\bar{n} = \nu$. At the Landau level below the chemical potential μ and at a temperature $kT << \mu - \varepsilon$, the statistics of quasiparticles (6) yields $\nu\bar{n} = 1$. Taking into account (2), we obtain the effective charge of the quasiparticle [3, 8].

$$e^* = \nu e \cdot \qquad (3)$$

The energy of the lower level, completely filled with quasiparticles, reaches a value of $\varepsilon^* = \frac{\hbar e^* B^*}{2m} = \nu^2 \varepsilon$. The conversion of electrons into quasiparticles rotating in cyclotron orbits is accompanied by the release of energy in the form of a pulse of infrared radiation. The circular frequency of the radiation is equal to the cyclotron frequency of quasiparticles $\omega_c^* = \frac{e^* B^*}{m} = \nu^2 \omega_c$. The energy balance $\hbar\omega_c^* n_\gamma S = (\varepsilon - \varepsilon^*) N_e$ gives the number of photons emitted $n_\gamma = n_S \frac{\varepsilon - \varepsilon^*}{\hbar\omega_c^*} = n_S \frac{1-\nu^2}{2\nu^2}$

The magnetic moment of quasiparticles per unit area $2p\Phi_1 n_S$ in an external field B^* has an energy

$$E_M(\nu) = 2p\Phi_1 n_S B^* = \nu(1-\nu)B^2. \qquad (4)$$

The magnetic energy of quasiparticles per unit area for semions at $\nu = 1/2$ reaches a maximum $E_M(\nu = 1/2) = B^2/4$.

3. Quasiparticle Statistics

For the filling factor $0 < \nu \le 1$, the average number of quasiparticles in one state $\bar{n} \equiv \overline{n_\nu(\varepsilon, T)}$ with energy ε in an ideal gas with temperature T is described by fractional statistics [5, 6, 9].

$$\bar{n} = \bar{n}_M (1-\nu\bar{n})^\nu [1+(1-\nu)\bar{n}]^{1-\nu}, \qquad (5)$$

where $\bar{n}_{\mathrm{M}}(\varepsilon)=e^{(\mu-\varepsilon)/kT}\equiv 1/x$. For energy below the level of chemical potential $\mu-\varepsilon=\zeta\to+0$ at $kT<<\zeta$, we obtain $x\to 0$ and from (5) we find

$$\bar{n}(\varepsilon<\mu)\cong 1/\nu\,. \tag{6}$$

Relation (6) ensures equality of the concentrations of the initial electrons and the resulting quasiparticles. When $\varepsilon-\mu=\zeta\to+0$, $kT<<\zeta$, we obtain $x>>1$ and from (5) when $\varepsilon>\mu$ we find

$$\bar{n}(\varepsilon>\mu)\approx 1/x=e^{-(\varepsilon-\mu)/kT}<<1\,. \tag{7}$$

For electrons, taking into account $p=0$, $\nu=1$, from (5) we find the Fermi – Dirac distribution

$$\bar{n}_1(\varepsilon)=\frac{1}{x+1}=\frac{1}{e^{(\varepsilon-\mu_1)/kT}+1}\,. \tag{8}$$

For bosons $\nu=0$ and (5) gives the Bose – Einstein distribution

$\bar{n}_0(\varepsilon)=\dfrac{1}{x-1}=\dfrac{1}{e^{(\varepsilon-\mu_0)/kT}-1}$, where $\mu_0\le 0$, $|\,\mu_0\,|<<kT$, then at low temperature

$\bar{n}_0(\varepsilon)=\dfrac{1}{x-1}\cong e^{-\varepsilon/kT}$.

For semions with $\nu=1/2$ from (5) we obtain

$$\bar{n}_{1/2}=\frac{1}{\sqrt{x^2+1/4}}\,. \tag{9}$$

For anyons with $p=1$, $\nu=1/3$, from (5) in the form $(4+27x^3)\bar{n}^3-27\bar{n}-27=0$ we find

$$\bar{n}_{1/3}=\frac{3}{\sqrt{1+27x^3/4}}\mathrm{ch}\frac{\theta}{3},\qquad \mathrm{ch}\theta=\sqrt{1+27x^3/4}\,. \tag{10}$$

At $\varepsilon=\mu$ from (8), (9), (10) we obtain

$$\bar{n}_1(\varepsilon=\mu_1)=0{,}5,\quad \bar{n}_{1/2}(\varepsilon=\mu_{1/2})\cong 0{,}894\,,$$

$$\bar{n}_{1/3}(\varepsilon=\mu_{1/3})\cong 1{,}252\,. \tag{11}$$

The population of the state at the level of chemical potential increases with weakening of the filling factor ν. The length of the transition region is proportional to the thermal energy, so for electrons $\Delta\varepsilon_1\cong 4kT$. For semions from (9) we obtain $\dfrac{2}{\Delta\varepsilon_{1/2}}\equiv-\dfrac{d\bar{n}_{1/2}}{d\varepsilon}\bigg|_{\varepsilon=\mu}=\dfrac{1}{(5/4)^{3/2}kT}$ and $\Delta\varepsilon_{1/2}\cong 2{,}795\,kT$. For anyons we find $\Delta\varepsilon_{1/3}\cong 1{,}497kT$. Therefore, when the filling factor decreases, the transition area narrows.

The phase space limitation gives the number of particles of a two-dimensional gas per unit area $n_S=\dfrac{2\pi m}{h^2}\int_0^\infty\bar{n}(\varepsilon)d\varepsilon$. At low temperature we use (6) and (7), then $n_S\cong\dfrac{2\pi m}{h^2\nu}\int_0^{\mu_\nu}d\varepsilon=\dfrac{2\pi m\mu_\nu}{h^2\nu}$. Taking into account the concentration of quasiparticles $n_S=\dfrac{eB}{h}\nu$, we find the chemical potential

$$\mu_\nu=\frac{2\pi\hbar^2 n_S}{m}\nu=\frac{\hbar eB}{m}\nu^2=2\varepsilon_\nu^*\,. \tag{12}$$

The Landau level of quasiparticles is two times lower than the level of chemical potential. For a fixed magnetic field and variable n_S and ν, we find $\mu_{1/2}=\mu_1/2$, $\mu_{1/3}=\mu_1/3$, $|\,\mu_0\,|<<kT$. A decrease in chemical potential means a weakening of the repulsion between particles. Distributions (8), (9), (10) are shown in Figure 1.

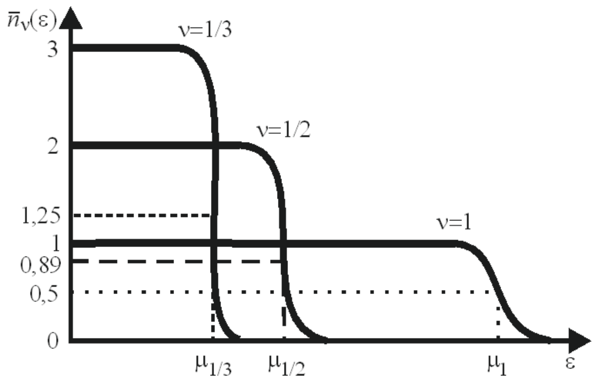

Figure 1. *Distribution functions of quasiparticles for* $kT<<\mu_\nu$.

4. Dispersion, Correlation and Bunching of Quasiparticles

We differentiate (5) with respect to the chemical potential $\dfrac{d\bar{n}}{d\mu}=\dfrac{1}{kT}\overline{(\Delta n)^2}$ and find from it the dispersion of the number of quasiparticles in one state [6]

$$D \equiv \overline{(\Delta n)^2} = \bar{n} + (1-2\nu)\bar{n}^2 - \nu(1-\nu)\bar{n}^3, \tag{13}$$

where $\Delta n \equiv n - \bar{n}$ is the deviation from the average distribution by state. The first term (13) describes shot noise, the second describes wave packet noise, reaching a maximum at $\nu \to 0$. The third term weakens the dispersion due to mutual interference repulsion of quasiparticles, reaching an extremum at $\nu = 1/2$. At energies much lower and much higher than the values of chemical potential, taking into account (6) and (7), we find $D = 0$. The dispersion is significant at $\varepsilon \approx \mu$ and increases with weakening of the filling factor: $D(\nu = 1) = 0{,}25$, $D(\nu = 1/2) = 0{,}715$, $D(\nu = 1/3) = 1{,}338$, therefore, statistical interference effects increase with weakening ν.

To obtain a correlation of the number of particles, we mentally divide the system of n particles into two subsystems with the numbers of particles n_1 and n_2. We substitute $n = n_1 + n_2$ and $\bar{n} = \bar{n}_1 + \bar{n}_2$ into the definition of dispersion $D \equiv \overline{(n-\bar{n})^2}$. Using the deviations from the mean $\Delta n_i = n_i - \bar{n}_i$ for subsystems $i = 1, 2$, we find the relationship between the dispersions of the numbers of particles in the subsystems $D_i \equiv \overline{(\Delta n_i)^2} = \overline{n_i^2} - \bar{n}_i^2$ and in the entire system

$$D = D_1 + D_2 + 2C_{12}, \tag{14}$$

where is the correlation between deviations from the mean in subsystems

$$C_{12} \equiv \overline{\Delta n_1\, \Delta n_2} = \overline{n_1 n_2} - \bar{n}_1\bar{n}_2 = K_{12} - \bar{n}_1\bar{n}_2, \tag{15}$$

correlation between particle numbers

$$K_{12} \equiv \overline{n_1 n_2} = C_{12} + \bar{n}_1\bar{n}_2. \tag{16}$$

Fluctuations in the number of particles in the subsystems have opposite signs and $C_{12} < 0$. The absence of correlation between the subsystems means maximum mutual interference repulsion of the particles, corresponding to $\min|C_{12}|$. When $|C_{12}| > \min|C_{12}|$, the particles attract each other.

To obtain an explicit form of the correlation, we substitute $\bar{n} = \bar{n}_1 + \bar{n}_2$ into expression (13), compare with (14) and (15), and find

$$C_{12} = \left[1 - 2\nu - \frac{3}{2}(1-\nu)\nu\bar{n}\right]\bar{n}_1\bar{n}_2. \tag{17}$$

The result depends on the method of dividing the particle system into subsystems.

In the general case, we divide the system into all possible parts with equal probabilities $\bar{n}_1 = \bar{n} - z$ and $\bar{n}_2 = z$, where $0 \le z \le \bar{n}$, then the average $\langle \bar{n}_1\bar{n}_2 \rangle = \bar{n}\langle z \rangle - \langle z^2 \rangle$. With equal probability, we find $\langle z \rangle \equiv \frac{1}{\bar{n}}\int_0^{\bar{n}} z\,dz = \frac{\bar{n}}{2}$, $\langle z^2 \rangle = \frac{\bar{n}^2}{3}$,

$$\langle \bar{n}_1\bar{n}_2 \rangle = \frac{\bar{n}^2}{6}. \tag{18}$$

We obtain the average correlation

$$\langle C_{12} \rangle = \left[1 - 2\nu - \frac{3}{2}(1-\nu)\nu\bar{n}\right]\frac{\bar{n}^2}{6}, \tag{19}$$

When $\varepsilon < \mu$ we use (6) and from (19) and (16) we obtain

$$\langle C_{12}(\nu) \rangle = -\frac{1+\nu}{12\nu^2}, \qquad \langle K_{12}(\nu) \rangle = \frac{1-\nu}{12\nu^2}. \tag{20}$$

The correlation modules increase with decreasing ν, as shown in Figure 2. When $\varepsilon > \mu$ we find, $\langle C_{12}(\nu) \rangle, \langle K_{12}(\nu) \rangle << 1$.

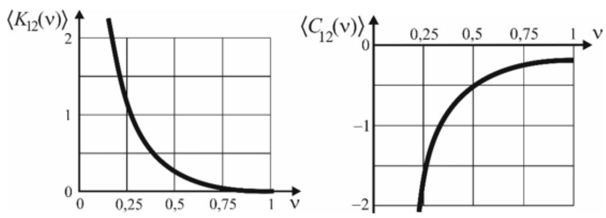

Figure 2. *Average correlations of quasiparticles for* $\varepsilon < \mu$.

For the integer Hall effect we obtain $\langle K_{12}(\nu = 1) \rangle = 0$, $\langle C_{12}(\nu = 1) \rangle = -0{,}167$, which corresponds to the mutual interference repulsion of fermions caused by the Pauli principle.

We define the second-order correlation function

$$g^{(2)}(\bar{n}) \equiv \frac{\overline{n_1 n_2}}{\bar{n}_1\bar{n}_2} = \frac{K_{12}}{\bar{n}_1\bar{n}_2} = \frac{C_{12}}{\bar{n}_1\bar{n}_2} + 1 \tag{21}$$

and the quasiparticle bunching coefficient [4]

$$N_b \equiv \frac{\overline{\Delta n_1 \Delta n_2}}{\bar{n}_1\bar{n}_2} = \frac{C_{12}}{\bar{n}_1\bar{n}_2}, \tag{22}$$

independent of the method of dividing the particle system into subsystems. From (15) we obtain $g^{(2)} - 1 = N_b$. Definition domains are $-1 \le g^{(2)} \le 1$, $-1 \le N_b \le 1$. When $-1 \le N_b < 0$ antibunching of quasiparticles takes place, when $0 < N_b \le 1$ it is bunching.

For a gas of classical independent particles with dispersion $D = \bar{n}$ from (14), we find a correlation between the fluctuations of the particle numbers $C_{12} = (\bar{n} - \bar{n}_1 - \bar{n}_2)/2 = 0$. From (15), (16) and (18) we obtain the correlation between the numbers of particles $K_{12} \equiv \overline{n_1 n_2} = \bar{n}_1 \bar{n}_2$ and the average correlation between subsystems $\langle K_{12} \rangle = \bar{n}^2 / 6$. From (21) and (22) we also find $g^{(2)} = 0$ and the absence of grouping $N_b = 0$ for classical particles.

For a gas of wave packets with dispersion $D = \bar{n}^2$ we find $C_{12} = (\bar{n}^2 - \bar{n}_1^2 - \bar{n}_2^2)/2 = \bar{n}_1 \bar{n}_2$, $K_{12} = 2\bar{n}_1 \bar{n}_2$, $\langle K_{12} \rangle = \bar{n}^2 / 3$, $g^{(2)} = 0$. Boson bunching reaches its maximum $N_b = 1$.

The third term in (13) corresponds to $D = -\bar{n}^3$, then $C_{12} = -3\bar{n}\bar{n}_1\bar{n}_2)/2$, $K_{12} = (1 - 3\bar{n}/2)\bar{n}_1\bar{n}_2$, $g^{(2)}(\bar{n}) = -3\bar{n}/2$ and there is an antibunching $N_b = -3\bar{n}/2$.

For the fractional quantum Hall effect with dispersion (13), from (22) we obtain the quasiparticle bunching coefficient

$$N_b(\bar{n}, \nu) = 1 - 2\nu \left[1 + \frac{3}{4}\bar{n}(1-\nu) \right]. \tag{23}$$

From (6) and (7) we find

$$N_b(\varepsilon < \mu_\nu) = -(1+\nu)/2, \tag{24}$$

$$N_b(\varepsilon > \mu_\nu) = 1 - 2\nu. \tag{25}$$

For $\varepsilon = \mu_\nu$ we use (11) and from (23) we find $N_b(\nu = 1) = -1$, $N_b(\nu = 1/2) = -0{,}335$, $N_b(\nu = 1/3) = -0{,}084$.

As a result, the quantum Hall effect gives

for electrons with $\nu = 1$: $N_b(\varepsilon < \mu_1) = -1$, $N_b(\varepsilon = \mu_1) = -1$, $N_b(\varepsilon > \mu_1) = -1$;

for semions with $\nu = 1/2$: $N_b(\varepsilon < \mu_{1/2}) = -3/4$, $N_b(\varepsilon = \mu_{1/2}) = -0{,}335$, $N_b(\varepsilon > \mu_{1/2}) = 0$;

for anyons with $\nu = 1/3$: $N_b(\varepsilon < \mu_{1/3}) = -2/3$, $N_b(\varepsilon = \mu_{1/3}) = -0{,}084$, $N_b(\varepsilon > \mu_{1/3}) = 1/3$;

for quasiparticles with $\nu << 1$: $N_b(\varepsilon < \mu_\nu) = -1/2$, $N_b(\varepsilon > \mu_\nu) = 1$.

The results are presented in Figure 3. For electrons, antibunching is maximum at any energy according to the Pauli principle for fermions. As the population of the level decreases, the number of magnetic flux quanta captured by the quasiparticle increases, antibunching weakens at any energy, and the Pauli principle for quasiparticles is violated, as follows from (6) at $\nu < 1$. Anyons occupy an intermediate position between fermions and bosons. The maximum number of quasiparticles in a single state is obtained from (6)

$$n_{\max} = 1/\nu. \tag{26}$$

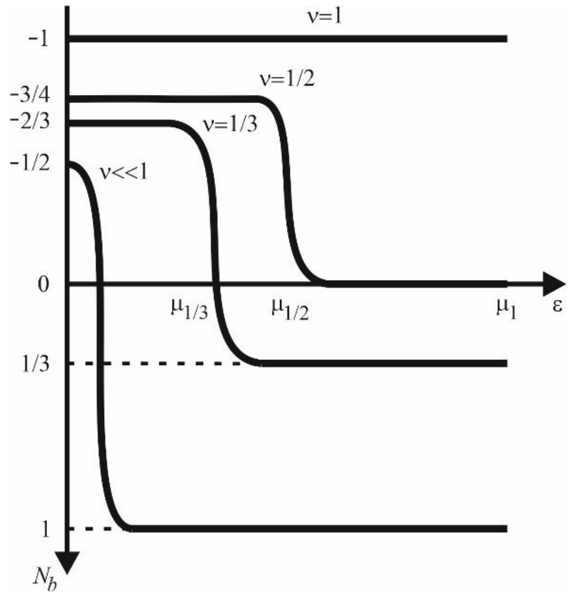

Figure 3. *Quasiparticles bunching coefficient.*

At energies above the chemical potential, antibunching disappears for semions, bunching appears for anions, and maximum bunching is achieved for boson quasiparticles with $\nu << 1$.

5. Experiments

If the electron gas in a semiconductor is converted into an anion gas with $\nu = 1/3$, then the energy of the system decreases ninefold, and $n_\gamma = 4n_S$ photons are emitted per unit area. The correlation between the quasiparticles of the subsystems increases from $\langle K_{12}(\nu = 1) \rangle = 0$ to $\langle K_{12}(\nu = 1/3) \rangle = 1/2$, when $\varepsilon < \mu$ the correlation between deviations from the average value of the number of quasiparticles changes from $\langle C_{12}(\nu = 1) \rangle = -1/6$ to $\langle C_{12}(\nu = 1/3) \rangle = -1$, and the antibunching of quasiparticles changes from $N_b(\nu = 1) = -1$ to $N_b(\nu = 1/3) = -2/3$.

A weakening of ν at $\varepsilon < \mu_\nu$ leads to a decrease in antibunching, mutual interference of quasiparticles, and an increase in bunching. This means that the diamagnetism of the electron gas is complemented by the paramagnetism of the quasiparticles.

As [7] showed in 2001, at low energy, the correlation of quasiparticles in semiconductors increases with decreasing level filling factor. The bunching of anyons compared to electrons has been confirmed by a number of experiments. The shot noise of anyons passing through a potential barrier was measured by [2] in 2002. At low current, the quasiparticles become rarefied, move individually, and the charge is detected $e^* = \nu e$. The correlation of the edge chiral currents of quasiparticles scattered in quantum dot contacts was studied in the work [1] in 2020, an effective charge was obtained and mutual attraction of quasiparticles was discovered.

Anyon statistics are discussed in [10].

The relevance of the topic is discussed in the context of cutting-edge experiments in [11].

Fractional Hall quantization in topological insulators is investigated in [12].

Bosonic analogues of the fractional Hall effect are considered in [13].

The hierarchy of fractional states is discussed in [14].

6. Dark Matter and Big Bang

The quantum Hall theory of an electron gas in a magnetic field at low temperature is applied not only to semiconductors, but also on a cosmological scale to describe the evolution of a model of the Universe in the form of an electron gas in a strong uniform magnetic field at low temperature. The filling factor (1) $\nu \cong \frac{hn_S}{eB}$ depends on the electron concentration n_S. In regions of space with small n_S / B, we obtain $\nu << 1$, and the Hall quasiparticles are bosons with an effective charge (3) $e^* = \nu e \to 0$. This means the absence of influence of quasiparticle levels other than the ground state and transitions between them, that is, the complete absence of electromagnetic interactions with quasiparticles in the form of emission, absorption and reflection of light. The quantum bunching of boson quasiparticles with $N_b(\varepsilon > \mu_{\nu<<1}) = 1$ leads to an increase in the density of matter with a completely captured external magnetic field according to (2) $B^* = \nu B \to 0$, and external charges creating it. The listed features are inherent in Dark Matter, which should be considered as ordinary matter in the fractional quantum Hall effect in the state of bosons. Dark Matter does not undergo heating during the process of evolution; its original temperature and internal state are preserved.

In regions of high concentration n_S caused by gravity, quasiparticles with $\nu > 0$ have a non-zero effective electric charge. External heating destroys the Hall state. The quasiparticle explodes, ejecting the trapped magnetic field and external charges, and transforms into an electron. A process of "cosmic inflation" occurs and a massive ejection of matter in the form of jets from areas of increased concentration n_S. The chaotic thermal motion of electrons creates chaotic magnetic fields and the release of energy in the form of the Big Bang. We find the released local magnetic energy density from (4) $E_M(\nu) = \nu(1-\nu)B^2$ with the maximum value $E_M(\nu = 1/2) = B^2 / 4$. The electron model of the Universe discussed above can be realized experimentally.

Author Contributions

Eugene Alexandrovich Krasnopevtsev: Conceptualization, Methodology, Resources

Conflicts of Interest

The author declares no conflicts of interest.

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