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BOSON FQHE STATE IN CUPRATE OXIDE INDUCED BY ZERO-POINT OSCILLATION AND MACROSCOPIC INTERFERENCE PHENOMENA DEMONSTRATING FRACTIONAL CHARGE

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It is pointed out that in cuprate high-temperature superconductor (HTS) with carriers with large //c zero-point energy, the fractional quantum Hall effect (FQHE) can appear even at room temperature when space charge and moderate localization are present. The experimental process for the infallible observation of the FQHE charge fractionality is described.

1. INTRODUCTION

A many-particle boson (or fermion pair) system in the ground state can assume two typical macroscopic quantum states (phase-definite state Ψ_Θ and particle-number definite state Ψ_N) satisfying $\Delta N \Delta\Theta = 1/2$, where they are connected with each other by transformation relationship. Ideal Ψ_Θ (Ψ_N) is realized when $t \gg U (t \ll U)$ where t is the energy of the particle transition between discretely quantized particle sites and U is the double occupancy energy in one site. Metal superconductivity in $t \gg U$ is a typical Ψ_Θ, where the materialization of Ψ_N durable for electrical measurement is very difficult. Concerning the study of HTS, the Hubbard energy ~ 10 eV is normally considered as U. In this study, however, we consider the situation where each quantum site includes several ($\geq$2) Cu ions with partial occupation (or occupied by fractional charges), and where $U \sim t$ in ideal bulk crystal. It is known experimentally that Ψ_Θ in HTS is very fragile against localization which tends to cause $t < U$. The fragility suggests the stability of Ψ_N in thin HTS crystal with localization where enough durability for electrical measurement is expected.

We note the following [1], [2] concerning the possible Ψ_N in the hole-carrier system in c-oriented $La_{2-x}Sr_x$ CuO_4 film with localization:

(i) Being confined in a CuO_2 layer with $//$c wave-function spreading $\Delta x(//\mathrm{c}) < 0.66$ nm, a carrier in ground state has zero-point energy $\Delta E(//\mathrm{c}) \sim \Delta p(//\mathrm{c})^2/2m \sim \hbar^2/2m\Delta x(//\mathrm{c})^2 \sim (0.1 - 1\mathrm{eV}) \sim E_\mathrm{F} \gg 300k_\mathrm{B}$, where x axis is $//$c;

(ii) Singlet pairing is favorable even at 300K because $\Delta p(//\mathrm{c})^2/2m$ reduces to $\Delta p(//\mathrm{c})^2/4m$ in the replacement $(m \to 2m)$;

(iii) Supposing parabolic confining potential at a CuO_2 layer at $x = \zeta d(\zeta = 1, 2, 3, ...; d$, separation), the zero-point carrier wave function in the layer takes the same form as the lowest level solution in Landau-gauge $\mathbf{A}^*$ = (0,$B^*(x - \zeta d), 0)$ in $//$c magnetic field $B^* \sim 10^{3-4}$T, which is strong enough to cause FQHE (a typical Ψ_N in $\perp B$ 2D carrier system)[3] even at room temperature;

(iv) The «gauge» $\mathbf{A}^*$ varies from CuO_2 layer to layer through its ζ dependence, and hence is incapable of making an effective field $\mathbf{B}^* = (0, 0, B^*)$. It was shown [1] that the existence of space charge («ground charge») $\pm\rho_0$ helps to construct a regime, where the ζ-dependent «gauges» are unified, materializing the effective magnetic field $\mathbf{B}^*$;

(v) In the regime the combination of Landau-gauge solutions leads to symmetrical gauge solutions, and hence Laughlin function [4];

(vi) Reducing Coulomb-energy in total system, 2D FQHE appears under the strong $\mathbf{B}^*$ even at room temperature on xy plane (x $//$c and y $//$current $\mathbf{j}$) with $\pm$ charged regions, where $\pm\rho_0$ makes no chemical potential gradient;

(vii) The singlet pairing caused by $\Delta E(//\mathrm{c})$ reduction provides boson type ground FQHE states [1] at «filling factor» $\nu \to$ x = 1/2k $(k = 1, 2, 3, ...)$;

(viii) Equating the «flux-quantum-site» area $2\pi l_0^2$ to 2 Cu-site area (in ac or xy plane) $2 \times 0.38 \times 0.66$ nm^2, we find «magnetic length» $l_0 = 0.28$ nm, $\mathbf{B}^*$ = 4.1 $\times 10^3$T and $\Delta E(//\mathrm{c}) \equiv \hbar\omega_b/2$ = 0.24 eV;

(ix) The introduction of moderate localization not only makes $t \ll U$ stabilizing the FQHE state, but also facilitates the observation of FQHE by fixing charge;

(x) The FQHE planes $\perp$ $\mathbf{B}^*$ may make a multi-layer-stacked array with separation tentatively equated to $t \sim \xi_{\mathrm{ab}} = 3.7$ nm [1, 2];

(xi) Since the z-axis can be taken in parallel with either a- or b-axes, a 3D FQHE state may be materialized in «multi-parallel-cross» shape superposing a- and b-axis stacks;

(xii) The «ground charge» density $\pm\rho_0$ is embodied by quasiparticle charge array with separation $\lambda_{\mathrm{S}} \sim 100$ nm [2];

(xiii) In a 3D Ψ_N as the «multi-parallel-cross» FQHE regime, we expect the negative-capacitance relationship $\tilde{\rho}/\tilde{\phi} < 0$ with external charge expulsion [1, 2], just as London equation $\tilde{\mathbf{A}} + \mu_0\lambda_L^2\tilde{\mathbf{j}} = 0$ in Ψ_Θ leads to $\tilde{\mathbf{j}}/\tilde{\mathbf{A}} < 0$ and Meissner effect, where $\tilde{\mathbf{j}}$ and $\tilde{\rho}$ are field-induced current and charge, and $\tilde{\mathbf{A}}$ and $\tilde{\phi}$ are variations of vector and scaler potentials, respectively.

We reported studies on the above properties using c-axis-oriented $La_{2-x}Sr_xCuO_{4-y}$ film where localization is intentionally introduced [1, 2]. Concerning $La_{2-x}Sr_xCuO_{4-y}$, it is known that x makes hole-carrier doping, and that the deoxidization in cooling at temperature T <700°C gives rise to small y, inducing carrier localization with slight doping effect less than 0.01. We show below the macroscopic quantum interference of the FQHE state observed in the $La_{2-x}Sr_xCuO_{4-y}$ film.

2. QUASIPARTICLE EXCITATION ENERGY

Consider a ground Laughlin state [4] for a $\perp\mathbf{B}^*$ 2D carrier system with particle charge Q_0 in field $\mathbf{B}^* = (0, 0, B^*)$ at filling factor $\nu = 1/m$ $(m = 2k + 1$ for fermion, and $m = 2k$ for boson (or fermion-pair) $(k = 1, 2, 3, ...))$. The quasiparticle excitation in FQHE system of spin-polarized (↑) 2D fermion gas was studied by Halperin [5], where is used the initial (lebel $s = 0$) parameter set [filling factor $\nu_0 = 0$, charge $q_0 = 1$ (expressed in the ratio to Q_0), angular momentum quantum $m_0 = 1$]. In boson system, however, we use an initial parameters set $[\nu_0 = 0, q_0 = 1, m_0 = 1/2]$. With $\nu_0 = 0$ condition the nominal double occupation condition $m_0 = 1/2$ may cause no Coulomb energy increase. In real experimental condition, the filling factor of the samples is always $\nu \to \mathrm{x} \ll 1$. Therefore we need not worry about Coulomb energy increase in the strong coupling system. Figure 1 shows the filling-factor ν dependence of the

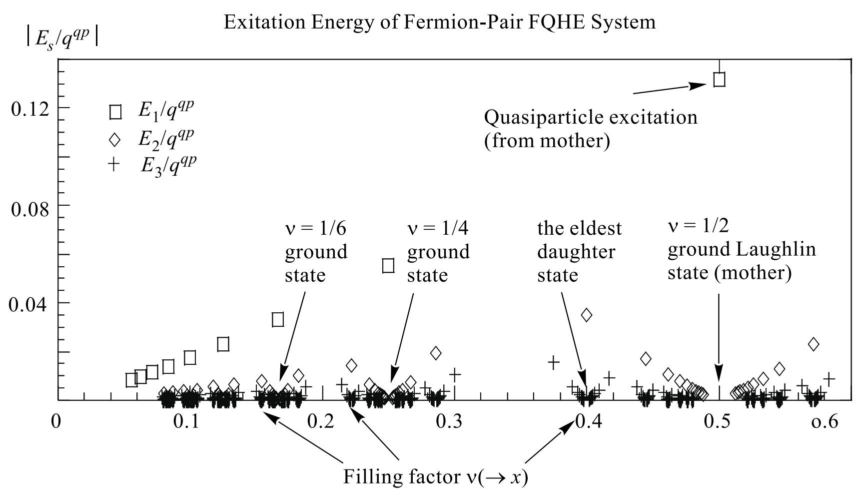

Fig. 1. The filling-factor ν dependence of the excitation energy E_s of singlet-hole-pair FQHE system. q^{qp} is the fraction of quasiparticle charge

calculated quasiparticle-excitation energy E_s (s, level) in the fermion-pair system, where $q_s^{\mathrm{qp}} \equiv Q_s^{\mathrm{qp}}/Q_0$ is the fraction of quasiparticle charge Q_s^{qp}. The ordinate unit is $e/\pi\varepsilon l_0$ (e electron charge, ε crystal-lattice dielectric constant, l_0 magnetic length). In Ref. 5 an empirical factor Λ = 3 is used concerning the excitation-energy ratio between «particle» and «hole». This parameter is tentatively put Λ = 1 in our calculation.

In Fig. 1 the ν values 0.15, 0.22, and 0.4 are denoted by up-pointing arrows, where is expected the co-existence of both a ground Laughlin (mother) state and its eldest daughter Laughlin state (see the example at $\nu = 1/2$), and where ($\nu \rightarrow$ x) the dielectric interference experiment described in the following section is made to demonstrate the existence of FQHE fractional charge. Since FQHE states of more descendent order may be unstable due to the smaller particle-particle interaction, we restrict our consideration only to the ground states and the eldest daughter states.

3. DIELECTRIC INTERFERENCE BETWEEN TWO INTERACTING LAUGHLIN STATES

We study the «dielectric interference» of two Laughlin states (= «electrode» Laughlin states) formed in the doubly charged regions in c-oriented $La_{2-x}Sr_xCuO_4$ film. The «electrode» states are connected via a neutral interface with a FQHE character slightly different from «electrodes» (see Fig. 2) [1, 2, 6]. The study of the inter-«electrodes» interference is made after Josephson effect [7]. We suppose that the «ground charges» $Q_x = Q^g N_x$ composed of quasiparticles have passed $//x$ across the interface from one «electrode» region to the other, and that flux quanta $\Phi_y = N_y \Phi_s (\Phi_s = h/Q_s^{\mathrm{L}})$ in the level s Laughlin state have traversed $//y$ along the interface. The phase is written $\Theta(N_x, N_y) = \hbar^{-1} \int dt[Q_x(d\Phi_y/dt) + \Phi_y(dQ_x/dt)] = 2\pi(Q^g/Q_s^{\mathrm{L}})N_x N_y$. Using the Q_x-definiteness of «electrodes» and a Hamiltonian $H\Psi_{N_y} = E_0\Psi_{N_y} + J_0(\Psi_{N_y+1} + \Psi_{N_y-1})$ with constant E_0 and J_0, we get energy $E(N_x) = E_0 + 2J_0\cos[2\pi(Q^g/Q_s^{\mathrm{L}})N_x]$ and voltage

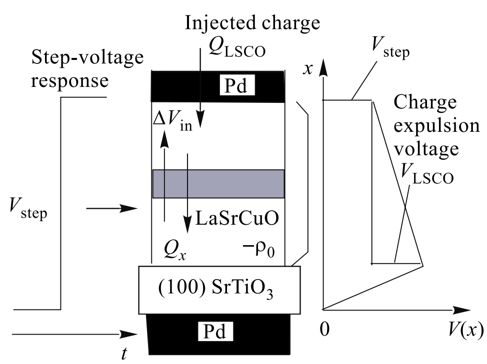

Fig. 2. Capactance element C_{t} having c-oriented $La_{2-x}Sr_xCuO_4$ film with naturally formed charge double layer

$$\Delta V_{\rm in} = \frac{d\Phi_y}{dt} = \Phi_s \frac{dN_y}{dt} = \frac{\Phi_s}{h}\frac{\partial E(N_x)}{\partial N_x} = -\frac{4\pi Q^g \Phi_s J_0}{hQ_s^{\rm L}}\sin(\frac{2\pi Q_x}{Q_s^{\rm L}}). \qquad (1)$$

Physical meaning of Eq. (1) is as follows. Both «electrodes» are stabilized when they accept Q_x of integral multiple of the Laughlin-particle charge $Q_s^{\rm L}$ of level s. Therefore the system induces pulling-back voltage $\Delta V_{\rm in}$ at the beginning stage of the cycle of charge passage ($N' \le Q_x/Q_s^{\rm L} < N' + \frac{1}{2}, N'$ integer) across the interface, and it induces an accelerating voltage $\Delta V_{\rm in}$ at the final stage ($N' + \frac{1}{2} < Q_x/Q_s^{\rm L} \le N' + 1$).

In Fig. 2 is schematically shown the capacitance element C_t used to measure the dielectric interference in the c-oriented $La_{2-x}Sr_xCuO_4$ with stacked array of xy 2D FQHE planes each of which is composed of $\pm$ charged FQHE regions connected by neutral interface [1, 2]. When $Q_{\rm LSCO} > 0$ is injected downward into $La_{2-x}Sr_xCuO_4$, a $//x$ charge-expulsion voltage $V_{\rm LSCO}$ appears inside the film keeping the relationship $Q_{\rm LSCO} = C_{\rm LSCO}V_{\rm LSCO}$. With the $Q_{\rm LSCO}$ injection the displacement $Q_x = Q_{\rm LSCO}$ of «ground charge» takes place across the interface. Since the «ground charge» is supposed to form 3D lattice structure with lattice constant $\sim \lambda_{\rm S}$ [2], we may divide the capacitance $C_{\rm LSCO}$ with total areas S into many small «sub-capacitances» each of which has area $\sim \lambda_{\rm S}^2$ and with the induced voltage of Eq. (1). With charge $(\lambda_{\rm S}^2/S)Q_x$ passage through the interface of each «sub-capacitance», the resultant capacitance $C'_{\rm LSCO}$ over area S has the following $V_{\rm LSCO}$ dependence with a constant V_0.

$$C'_{\rm LSCO}(V_{\rm LSCO}) \equiv \frac{Q_{\rm LSCO}}{V_{\rm LSCO} + \Delta V_{\rm in}(Q_x)} \simeq$$

$$\simeq C_{\rm LSCO}\left(1 - \frac{V_0}{V_{\rm LSCO}}\sin\Big(\frac{2\pi V_{\rm LSCO}}{SQ_s^{\rm L}/\Big|C_{\rm LSCO}\Big|\lambda_{\rm S}^2}\Big)\right). \qquad (2)$$

Thus a Fraunhofer pattern should appear in $C'_{\rm LSCO}(V_{\rm LSCO})$ with constant $C_{\rm LSCO} < 0$, where the pattern period $\Delta V = SQ_s^{\rm L}/\Big|C_{\rm LSCO}\Big|\lambda_{\rm S}^2 \propto Q_s^{\rm L}$.

The following must be noted for the infallible observation of charge fractionality: (i) On ideally $dielectric$ (at $\omega < 10^5{\rm s}^{-1}$) 1mm (100) $SrTiO_3$ substrate, make by sputtering good c-oriented $La_{2-x}Sr_xCuO_4$ films of x$\approx 0.15, 0.22, 0.40$ of special thickness $t_{\rm LSCO}$ (e.g., at x$\approx 0.15, t_{\rm LSCO} \approx 60, 100$nm) removing oxygen in cooling stage [1]; (ii) Make samples with $C_{\rm t}$ and $C_{\rm LSCO}$ elements with identical area; (iii) Select large $C_{\rm t}/C_{\rm LSCO}$ value samples ($C_{\rm t}/C_{\rm LSCO} \sim$ 1.2-1.5: 20-30% yield due to difficulty of uniform crystal formation) by ac measurement at 300K; (iv) Measure equilibrium charge $Q_{\rm t}$ and $Q_{\rm STO}$ stored in $C_{\rm t}$ and $C_{\rm STO}$

after several sec application of step voltage $V_{\rm step}$; (v) Considering the notable field dependence of $SrTiO_3$ dielectric property and the continuity of dielectric flux density **D**, find $C_{\rm LSCO} = Q/V_{\rm LSCO}$ at $Q = Q_{\rm t} = Q_{\rm STO}$ (see Fig. 3); (vi) Suppress the leakage current of $C_{\rm t}$ element less than 1 pA to obtain correct capacitance data.

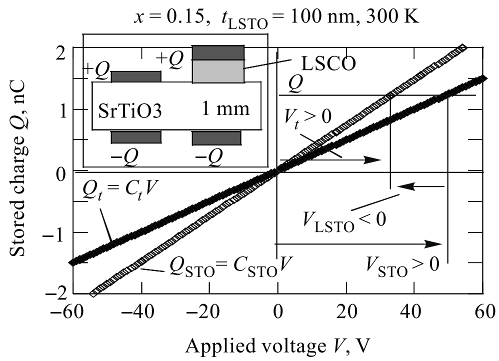

Fig. 3. The determination of $V_{\rm LSCO}$ and $V_{\rm STO}$ from charge-voltage-relationship data of $C_{\rm t}$ and $C_{\rm STO}$ elements

In Fig. 4 are exemplified the Fraunhofer patterns observed at room temperature when x = 0.15, 0.22, and 0.4. The following are noted: a) The superposed interference patterns are observed; b) The ratio of voltage-period ΔV of the superposed patterns just coincides with the expected ratio of $Q_s^{\rm L}$'s for coexisting mother (s=1) and the eldest daughter (s=2) state; c) Corresponding to FQHE theory where bulk current flows when $\left|Q_s^{\rm L} V_{\rm LSCO}\right| > \hbar\omega_{\rm b}$, the interference patterns suffer impairment in low $\left|V_{\rm LSCO}\right|$ region, which effect is intensified especially at lower temperature (77K, 4.2K); d) The centre peaks of the mother and daughter states appear in phase in the cases x = 0.15 and 0.4, and *out of phase* in x = 0.22 case, which may be related to the statistically different property at x $\simeq 1/4k$ and x $\simeq 1/2(2k+1)$; e) Using values $S = 7 \times 10^{-6}{\rm m}^2$, $\Delta V \approx 10$V (for $q_s^{\rm L} = 1$), $\left|C_{\rm LSCO}\right| \approx 10^{-10}$F, we find from Eq. (2) $\lambda_{\rm S} \approx 1.5 \times 10^{-7}$m, showing good agreement with theoretical estimation for $\lambda_{\rm S}$ [1, 2]; f) The fractionally charged particles can only survive in FQHE atmosphere, which prevents the observation of the charge fractionality in HTS using ordinary tunneling devices with insulator barrier [6].

4. CONCLUSION

The macroscopic interference in c-oriented $La_{2-x}Sr_xCuO_4$ film with localization is studied. The experimental process for the infallible observation of charge fractionality is described. The quasi-static measurement of capacitance of the $La_{2-x}Sr_xCuO_4$ film with localization reveals interference patterns with period proportional to Laughlin particle charges. The observation supports the model of HTS with localization in which boson-type FQHE is established under the strong effective magnetic field caused by the large //c zero-point energy and space charge.

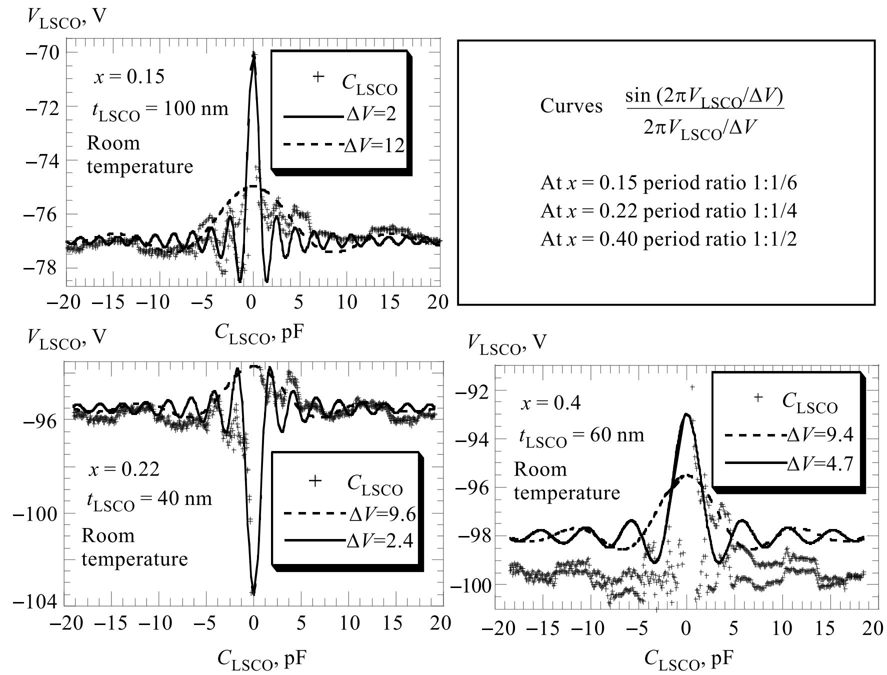

Fig. 4. The dielectric Fraunhofer patterns found in the capacitive devices in Fig. 2 when x=0.15, 0.22, and 0.4. The observed period ratios of the superposed patterns are shown in the inset table, which coincides with the ratios of the fraction of Laughlin charge $q_s^{\rm L} = Q_s^{\rm L}/Q_0$ expected from theory [4]

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