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Effect of the electromagnetic environment on the dynamics of charge and phase particles in one-dimensional arrays of small Josephson junctions

I. L. Ho\(^1\), W. Kuo\(^2\), S. D. Lin\(^3\), C. P. Lee\(^3\), C. T. Liang\(^4\), C. S. Wu\(^5\)(a) and C. D. Chen\(^1,6\)

\(^1\)Institute of Physics, Academia Sinica - Taipei 115, Taiwan
\(^2\)Department of Physics, National Chung Hsing University - 250, Taichung, Taiwan
\(^3\)Department of Electronic Engineering, National Chiao-Tung University - Hsinchu 300, Taiwan
\(^4\)Department of Physics, National Taiwan University - Taipei 106, Taiwan
\(^5\)Department of Physics, National Chang-Hua University of Education - ChangHua 500, Taiwan
\(^6\)Department of Physics, National Chen-Kung University - Tainan 701, Taiwan

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Abstract – The effect of the electromagnetic environment on the dynamics of quasi-particles, Cooper pairs and phase particles in one-dimensional arrays of small Josephson junctions is investigated experimentally and theoretically. It is found that the environment enhances the phase ordering and thus suppresses quasi-particle tunneling at high temperature and localization of Cooper pairs at low temperature. The dynamics is studied in the context of phase-charge duality, and the experimental results are quantitatively analyzed in both charge-ordered and phase-ordered regimes. Based on these analyses, a low-temperature phase diagram as well as a finite-temperature crossover phase diagram are constructed and compared to the experimental diagrams.

The competition between phase-order and charge-order in superconducting systems containing small grains has been a long-standing yet fascinating subject of interest [1–6]. Strong inter-grain Josephson coupling locks the phase difference, and the system is in the phase-order regime. Conversely, strong Coulomb interaction suppresses inter-grain charge tunneling, and the system is in the charge-order regime. Upon cooling from high temperature, the competition results in a continuous evolution from superconducting to quasi-reentrant [7] and to insulating regimes provided that the strength of the Josephson coupling is comparable to that of the Coulomb interaction. However, the Josephson coupling and the Coulomb interaction are affected by the presence of external parameters such as quasi-particles [8] and electromagnetic environment [3]. Recent theoretical [9–12] and experimental [13–15] advances revealed the important role of the electromagnetic environment on the fluctuations of phase and charge particles. In the phase-order regime, the electromagnetic environment can be considered to produce dissipation to the phase fluctuations and to support global superconductivity [16], which can eventually lead to dissipative-phase transition [17]. In the charge-order regime, it provides electromagnetic energy needed for virtual tunneling in the Coulomb blockade regime and promotes charge transport [18]. A system consisting of lithographically made small Josephson junctions [19,20] provides a paradigmatic model for studying this competition because here the charging energy can be designed precisely while the Josephson coupling energy can be controlled independently. The one-dimensional Josephson junction array (1D JJA) is an ideal system in which each junction is virtually decoupled from the measurement leads. The superconductor-insulator (SI) transition in 1D arrays of small Josephson junctions was previously explored [21] where the transition is controlled by tuning the Josephson coupling strength. Here, in addition to that, we show that the SI transition can also be tuned by

\(^{(a)}\)E-mail: wuc@cc.ncue.edu.tw
changing the impedance of the electromagnetic environment. This is of particular interest as it provides a direct test of the theory of dissipative-phase transition [17].

Using the 1D JJA as an example, in this work we study the effects of a two-dimensional electron gas (2DEG) environment [22,23] on the quasi-reentrant behavior, which reflects directly the dynamics of quasi-particles, phase particles and Cooper pairs. Experimentally, the Josephson coupling strength is varied by an applied magnetic field while the environment strength, which is inversely proportional to the impedance of the underneath 2DEG sheet, is controlled by a pair of side-gates. Being able to tune both the Josephson coupling and the environment strength independently, we mapped out a low-temperature quantum phase diagram [24] in which the region for the quasi-reentrant behavior is identified. The quasi-reentrant behavior is characterized by two resistance turnover temperatures which divide the temperature dependence into three distinct regimes: from low temperature, they are charge-order regime, phase-order regime and quasi-particle dominating regime. Lowering the environment impedance will decrease the quasi-reentrant behavior.

1D arrays comprising 100 aluminum SQUIDs (see inset of panel (A2) in fig. 1) are made on the top of a GaAs/AlGaAs hetero-structure, about 100 nm above the 2DEG sheet. Each SQUID consists of two parallel Josephson junctions with a junction area of 80 × 180 nm², corresponding to a sum junction capacitance C of about 1.5 fF [25] and a charging energy $E_{CP} \equiv 4e^2/2C$ of about 212 μeV. The arrays are fabricated by standard e-beam lithography and tilted-angle evaporation techniques as addressed in the previous works [19,21]. While the two arrays (denoted as A and B) present here have the same junction area, the junction resistances are different because of the difference in the tunnel barrier thickness. The Josephson coupling energy $E_{J0}$ can be determined by using the Ambegoakar-Baratov relationship, $E_{J0} \equiv (\Delta/2)(R_Q/R_N)$. Here, $R_Q \equiv h/4e^2 \approx 6.45$ kΩ is the quantum resistance, $R_N \approx (6.75$ kΩ for A and 7.7 kΩ for B) is the measured normal state resistance of each SQUID (i.e. two parallel junctions) and $\Delta = 200$ μeV is the superconducting energy gap. The normal state resistance can be controlled by the oxidation time of the bottom Al electrode before vaporization of the top Al electrode. Accordingly, $E_{J0}$ of the SQUIDs in arrays A and B is 96.3 μeV and 83.8 μeV, respectively. The 2DEG sheet possesses a carrier concentration of about $5 \times 10^{11}/$cm², yielding a sheet resistance $R_0$ of about 80 Ω at 80 mK. The 1D arrays are placed at the center of a pair of side-gate electrodes which confines the underneath 2DEG sheet into a long strip. The capacitance $C_0$ between each superconducting island and 2DEG is estimated to be $\sim 0.47$ fF. The 2DEG structure is similar to that in ref. [23] except that in this work the backgate is replaced by a pair of metal side gates. The two ends of the strip are connected to Au pads via Ohmic contacts for measuring the 2DEG resistance. Through these Ohmic contacts, the zero-bias resistance of the 2DEG strip could be measured using a separated AC lock-in circuit. The gap between the two side-gates is about 5 μm whereas the width of the 1D SQUID arrays is 1 μm. The electrons in the strip were depleted by application of a negative voltage on the side-gates, causing an exponential increase in the 2DEG sheet resistance. The arrays were placed in a compartment in a dilution refrigerator equipped with a superconducting magnet, and the electric characterization was performed by using a symmetrical source-meter circuit to minimize any possible pick-up of common mode noises. The zero-bias resistance of the arrays was extracted from the current-voltage $(I-V_0)$ traces taken at varying magnetic fields, side-gate voltages, and temperatures. A perpendicularly applied magnetic field $B$ threading the SQUIDs with loop area A could reduce the Josephson coupling energy to $E_J = E_{J0} \cos(\pi B \times A/\Phi_0)$;
here $\Phi_0 \equiv h/2e$ is the flux quantum. The magnetic field corresponding to a flux quantum in the loop is about 42.5 Gs. The side-gate field has no measurable effect on the arrays themselves with similar $E_{J0}$ and $E_{CP}$ values; this was confirmed separately on other 1D arrays made on bulk silicon chips. For a quantitative analysis, the strength of the environment is defined by a dimensionless conductance, $\alpha \equiv R_0/R_{2DEG}$.

Figure 1 illustrates the similarity between the effects of changing $E_J$ and $\alpha$ on the I-V$_b$ characteristics at low temperatures: decreasing $E_J$ and $\alpha$ tends to suppress the critical current and to enhance the Coulomb blockade of Cooper-pair tunneling. However, it is noticed that the influence of $\alpha$ is prominent when the device $E_J/E_{CP}$ value is tuned to be between 0.2 and 0.3 where both phase and charge fluctuations are significant. The small difference in the switching currents shown in panel (B$_1$) is an indication of the uniformity of the junction parameters in the 1D arrays. The inset in fig. 2(a) shows a low-temperature phase diagram for array A with borders determined by the trend of $R_0(T)$ at $T = T_{min}$ ($T_{min} \approx 100$ mK in the experiment). The phase diagram is largely divided into superconducting regions I (d$R_0$/d$T$ $|_{T=T_{min}} > 0$) and insulating regions II and III (d$R_0$/d$T$ $|_{T=T_{min}} < 0$). However, here we are interested in region II in which the $R_0(T)$ characteristics exhibit a downturn at $T_h$ and then an upturn at $T_l$ upon cooling. As shown in the inset in panel (B$_2$) of fig. 1, array B also exhibits a similar behavior. The upturning between $T_h$ and $T_{min}$ is a characteristic known as quasi-reentrant behavior, as shown in fig. 2(a). Figure 2(b) displays the I-V$_b$ as well as the differential conductance ($G_d \equiv dI/dV_b$) vs. $V_b$ curves at $T_h$, $T_l$ and $T_{min}$. We note a clear evolution from governing Josephson tunneling at $T_h$ to onset of Coulomb blockade of Cooper-pair tunneling at $T_l$ and then to strong localization of Cooper pairs at $T_{min}$. Figure 2(a) also shows the $R_0(T)$ at different $\alpha$. As $\alpha$ is increased, $R_0$ at all temperatures decreases; this is attributed to the suppression of phase fluctuations (in the phase-order regime) as well as enhanced higher-order tunneling (in the charge-order regime). Moreover, we find that $T_h$ increases and $T_l$ decreases with increasing $\alpha$.

For a quantitative analysis of the quasi-reentrant behavior, $T_h$ and $T_l$ are calculated theoretically. The Lagrangian of the system comprises items for an 1D JJA, a 2DEG sheet and the interaction between them and is given by [17,26]

$$L_{total} = L_{JJA} + L_{2DEG} + L_{interaction} =$$

$$\frac{1}{2} \sum_{ij} Q_{ij} \left[ \left( \hat{C}^{-1} \right)_{ij} + \left( \frac{1}{4e^2} \frac{3\pi}{32\Delta R_{ij}} \right) \right] Q_{ij}$$

$$+ \sum_{\langle i,j \rangle} E_J [1 - \cos(\varphi_i - \varphi_j)] + \frac{1}{2} \sum_{n} \left( m_n \dot{x}_n^2 - m_n \omega_n^2 x_n^2 \right)$$

$$- \sum_{i>n} F_{in} (Q_i, \varphi_i, x_n, \lambda_{in}) \quad (1)$$

The 2DEG environment is represented by an ensemble of harmonic oscillators with resonant (Matsubara) frequencies $\omega_n \equiv 2\pi nk_BT$ [17]. In the last term, $\lambda_{in}$ describes the coupling strength between superconducting island $i$ and environment oscillator $n$. For simplicity, we model the 2DEG sheet as an Ohmic environment [27] by applying a constraint [26,28],

$$\sum_{n} \frac{\pi \lambda_{in}^2}{2m_n} \delta (\omega - \omega_n) = R_{2DEG}. \quad (2)$$

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This model is applicable for frequencies below the junction plasma frequency, which is about 300 GHz (or 14 K in temperature).

In the charge presentation, the $E_J$ (i.e. the 2nd) term is treated as a perturbation to the charge states and the environment (the 3rd and 4th) terms are taken into account by the $P(E)$ theory [18]. The tunneling rates for Cooper pairs (CPs) and quasi-particles (QPs) are given by the Fermi-Golden rule approximation [18]:

$$\gamma_{CP} = \frac{\pi}{2\hbar} E_J^2 \bar{P}(\delta E_{ch,CP}),$$

$$\gamma_{QP} = \frac{1}{e^2 R_{J}} \int_{-\infty}^{\infty} dE' \int_{-\infty}^{\infty} dE' \bar{N}(E) \bar{N}(E') f(E) [1 - f(E')]$$
$$\times \bar{P}(\delta E_{ch,QP} + E' - E);$$

where $\bar{P}(E)$ is the probability function describing the exchange of energy $E$ between environment and Cooper-pairs tunneling. For quasi-particles, this probability function is denoted as $P(E)$, $N(E) = \Theta(|E| - \Delta)$ is the BCS density of states with a superconducting gap $\Delta$ and $f(E)$ is the Fermi-Dirac distribution. $\delta E_{ch,CP}$ and $\delta E_{ch,QP}$ are the energy changes associated with the tunneling of the Cooper pairs and quasi-particles, respectively. Although $\gamma_{CP}$ and $\gamma_{QP}$ are the tunneling rates for a single junction in the 1D array, the charge statuses of all islands in the array enter via the arguments $\delta E_{ch,CP}$ and $\delta E_{ch,QP}$. In this way, the net tunneling rate $\Gamma$ for a junction is affected by the tunneling in the rest of the junctions and a correlation in the tunneling events is automatically established. Based on these two equations, the net tunneling rates at varying $\alpha$ and $T$ can be calculated using the Monte Carlo technique and the result for $\Gamma_{CP} - \Gamma_{ch}$, $\Gamma_{QP}$ - $\Gamma_{ch}$ are displayed in figs. (a) and (b), respectively. Details of the calculation technique are given in ref. [29]. $\Gamma_{CP} - \bar{\Gamma}_{ch} \Gamma_{QP} - \bar{\Gamma}_{ch}$ represent the net tunneling rates for right-moving Cooper pairs and quasi-particles, which can be converted to current by simply multiplying the corresponding Coulomb charges. In panel (a), the temperatures corresponding to the maximum $\bar{\Gamma}_{CP} - \bar{\Gamma}_{ch}$ are marked by vertical arrows and are identified as $T_i$. Below $T_i$, $\bar{\Gamma}_{CP} - \bar{\Gamma}_{ch}$ decreases due to the Coulomb blockade of the Cooper-pair tunneling. Above $T_i$, $\bar{\Gamma}_{CP} - \bar{\Gamma}_{ch}$ is suppressed due to the thermal fluctuations of the island superconducting phase which follows a $\coth(1/T)$-dependence [18] as addressed in the $P(E)$ theory. It is noted that the reentrant behavior exists even in the absence of quasi-particle tunneling (see the black dotted curve). The introduction of quasi-particle tunneling would affect the Cooper-pair tunneling in two ways (cf. the blue solid curve): Firstly, it would reduce the Cooper-pair tunneling rate because CP and QP tunneling are two competing processes as far as the charging effect is concerned. Secondly, it gives rise to an additional dissipation to the phase fluctuations [30] and decreases $T_i$. On the other hand, since $\alpha$ represents dissipation to the phase fluctuations, reducing $\alpha$ would raise $T_i$, as indicated by the red arrow. Regarding the downturn dependence at high temperature, $T_h$ can be identified as the temperature at which a sharp increase in the quasi-particle tunneling rate appears, as shown in fig. 3(b). Above $T_h$, thermally assisted tunneling of quasi-particles gains importance and the transport is described by a simple activation behavior. The effect of the environment on $T_h$ can be understood through the Cooper-pair tunneling rate by comparing the blue and red curves in fig. 3(a). Fast Cooper-pair tunneling, as in the case of large $\alpha$, would suppress quasi-particle tunneling and raise the $T_h$ value. Based on these calculations, the array resistance at varying temperatures for different $\alpha$ is obtained and displayed in fig. 3(c), which exhibits a good agreement with the measurement results shown in fig. 2(a).

In the phase presentation, the Lagrangian is analyzed in the context of phase localization in the Josephson potential well [31]. Similar to the Ginzburg-Landau mean-field theory for 2D and 3D junction arrays [32], the 1D JJAs are identified to be in the insulating phase when the phase correlation vanishes: $(E_J \cos \varphi_{ij}) = 0$. The presence of the environment (i.e. $\alpha \neq 0$) introduces an effective reduction to $E_{CP}$ by a factor of $\sqrt{1 + \alpha E_{CP}/2\pi \omega_n}$. For $T \rightarrow 0$, as
regions: a high-temperature resistive region, an intermediate superconducting region and a low-temperature insulating region. For a comparison, fig. 4(b) shows an experimental crossover phase diagram. This diagram can also be understood in charge presentation: For $T > T_h$, the increased quasi-particle tunneling suppresses the phase correlation and the array is pushed toward the resistive region. For $T < T_h$, Cooper pairs are more localized, resulting in strong fluctuations of phase and the array is thus moved toward the insulating region.

Outside the quasi-reentrant region, we show an additional horizontal crossover surface (shown in green), which is referred to as $T_m$. This surface separates the diagram into a low-temperature “insulating” region and a high-temperature “conductive” region. The experimental criterion for $T_m$ is the appearance of a dip structure in the differential conductance ($G_\alpha \equiv dI/dV_b$) vs. $V_b$ curve at the zero-bias point; see, e.g., orange and green traces in fig. 2(b). Within our measurement resolution, $T_m$ seems to overlap with the $T_l$ surface. The $T_m$ surface as a function of $E_J/E_{CP}$ and $\alpha$ can also be calculated in the charge presentation addressed above and the result is shown in fig. 4(a). The calculated Cooper-pair current shows a power-law dependence on $V_b$ as $I \sim V_b^\phi$ at low bias voltages, and a border given by $a = 1$ separates the regions of bound charges ($a > 1$) and free charges ($a \leq 1$) [31], which correspond to the insulating and conductive regions, respectively.

In summary, the effect of electromagnetic environment on the dynamics of charge and phase particles is studied by analyzing the quasi-reentrant behavior. By modeling the environment as an ensemble of harmonic oscillators, we calculated a finite-temperature crossover phase diagram, which agrees quantitatively with the experimental results. This study provides a leap toward understanding the effect of the electromagnetic environment on the phase-charge duality.

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