The Macroscopic Quantum Coherence Experiment

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Abstract

Superconducting devices based on the Josephson Effect are an important test bed for the study of macroscopic quantum phenomena, and are promising candidates for the implementation of quantum computers. In this work it is presented the research activity in this field of the Rome Macroscopic Quantum Coherence Group, promoted in the early 90's by Prof. Giordano Diambrini Palazzi.

Sometimes a student of Physics during his studies encounters "turning points", moments when different elements of knowledge suddenly connect together with the effect of a wider and deeper understanding of the matter and a complete change of the point of view. Behind such moments there are typically teachers with a strong passion for Physics and with a great talent for transmitting this passion. Prof. Diambrini Palazzi was one of them. The collaboration with him started in occasion of my undergraduate thesis, with a theoretical investigation concerning the possibility to produce and detect Gravitational Waves (GW) in a "laboratory" ideal experiment [1], in close collaboration with Dr. Daniele Fargion for the "hard theory" contribution. This subject was outside the ordinary experience of Prof. Diambrini Palazzi, but he was characterized by a love for all physics, which he called "aesthetically beautiful", and a great and humble scientific curiosity that led him to explore and study very different questions. After the conclusion of this research activity, with the identification of perspectives and limits for such an ideal experiment, the interest of Diambrini Palazzi moved toward a different field, the study of Macroscopic Quantum Coherence in superconducting devices. In 1994 he was the promoter of a project in this direction, supported by INFN and gathering different experts in the field of superconductivity, Josephson devices, cryogenics and Quantum Mechanics [2, 3]: Carlo Cosmelli from the University of Rome "La Sapienza", Maria Gabriella Castellano, Roberto Leoni and Guido Torrioli from IESS-CNR, Pasquale Carelli from the University of L'Aquila, in close

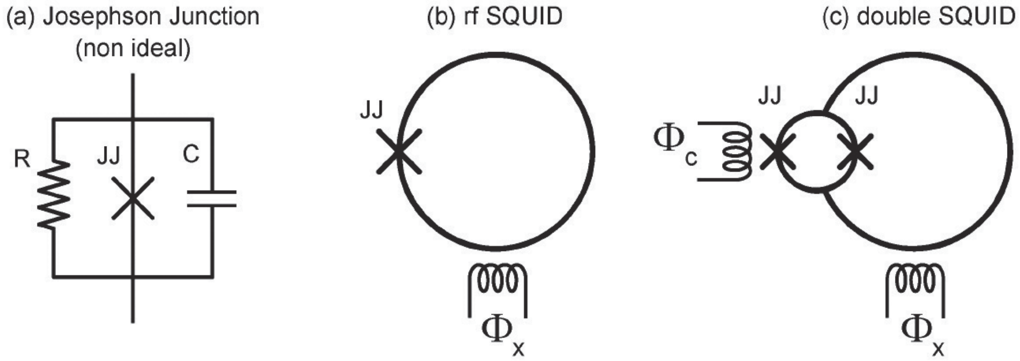

Figure 1: Schemes of a non ideal Josephson junction (a), an rf SQUID (b), and a double SQUID (c).

collaboration with part of the great and important group of Antonio Barone in Naples, and with the fundamental help of many other people, Gian Carlo Ghirardi of the University of Trieste and Mario Rasetti from the Politecnico of Torino just to name a few. This activity has continued till now, with important results and with the emergence of new objectives and directions, but always permeated by the curious and fascinated spirit of Prof. Diambrini Palazzi. In the following we briefly summarize the relative main points, with results and perspectives.

At the beginning of 90's, some macroscopic quantum effects in superconducting devices, such as Macroscopic Quantum Tunnelling [4] and Energy Level Quantization [5], had been already observed, but the direct observation of the coherent superposition of macroscopic quantum states presented serious experimental and conceptual difficulties [6, 7]. Superconducting devices allow the implementation of a flexible nonlinear electronics based on the Josephson Effect [8]. A Josephson junction consists of two superconducting electrodes separated by a thin insulating barrier (of the order of few nanometers). Cooper pairs (the supercurrent carriers) pass the barrier thanks to the tunnel effect, with a current $I_J = I_0 \sin\varphi$ (where φ is the phase difference of the order parameter between the two electrodes), and a voltage across the electrodes $V = \Phi_b d\varphi/dt$ (where $\Phi_b = \hbar/(2e)$ is the reduced flux quantum). Similarly it is possible to describe the supercurrent passing through different passive devices in terms of the phase difference: $I_C = C\Phi_b d^2\varphi/dt^2$ for a capacitance C, $I_R = (\Phi_b/R)d\varphi/dt$ for a resistance R, and $I_L = (\Phi_b/L)\varphi$ for an inductance L. In a non ideal Josephson junction also spurious effects must be considered; they can be modelled by the parallel of an ideal junction, a capacitance (due to the faced superconducting electrodes), and a resistance (describing losses in the barrier) (fig.1a). In a superconducting closed loop the threading magnetic flux

Φ must be quantized: $\Phi = \Phi_x - LI = n\Phi_0$ (where Φ_x is an applied magnetic flux, I the supercurrent circulating in the loop of inductance L, and $\Phi_0 = h/(2e) = 2\pi\Phi_b$ is the flux quantum). An rf SQUID (radio frequency Superconducting Quantum Interference Device) is a superconducting device consisting of a superconducting loop interrupted by a (non ideal) Josephson junction (fig.1b). The rf SQUID behaviour is described by an equivalent mechanical model, with an effective mass $M = C\Phi_b^2$ moving along a fictitious coordinate φ with damping $\gamma = 1/(RC)$ in the potential:

$$U = E_L \left[\frac{(\varphi - \varphi_x)^2}{2} - \beta \cos\varphi \right] \tag{1}$$

with $\varphi_x \equiv \Phi_x/\Phi_b$, $E_L \equiv \Phi_b^2/L$ and $\beta \equiv LI_0/\Phi_b$. The possibility to apply an equivalent mechanical model is a common feature in Josephson systems and it is supposed that for low enough temperatures such kind of systems could present a quantum behaviour, a sort of "second quantization" (different from the first that concerns the Cooper pairs quantum description). Notice that this is a very strong point, since the quantum state relative to the variable φ is related to a large number of Cooper pairs (of the order of 10^{11} in our cases), so that in this sense this is a macroscopic quantum state (something similar to a "Schrödinger cat"), even if it continues to be microscopic in the phase space [6]. In the present times there are a lot experimental indications in favour of this assumptions, even if there are still doubts that require to be addressed [9].

Going back to the rf SQUID, for $\varphi_x = \pi(\Phi_x = \Phi_0/2)$ and $\beta > 1$ the system is metastable and the potential in eq.(1) has a symmetric double well shape, with two minima separated by a central barrier. In this case, if the quantum limit holds, the system should be subject to quantum coherent oscillations between the two minima, corresponding to oscillations between two distinct magnetic flux states with frequency depending on the barrier height. A different device, the double SQUID, enables the practical implementation of an experiment for the detection of such oscillations (fig.1c). In this case the single junction is replaced by a dc SQUID, a small superconducting loop of inductance l interrupted by two identical junctions with critical current i_0 and capacitance c, biased by a second magnetic flux Φ_c. For $li_0 \ll \Phi_b$ the dc SQUID behaves approximately as a single junction with total capacitance $C = 2c$ and tuneable critical current $I_0 = 2i_0 \cos(\pi\Phi_c/\Phi_0)$. In this limit the double SQUID presents the same potential given in eq.(1), but with a controllable critical current, corresponding to a controllable barrier height. In an ideal experiment the system is initially prepared in one of the two flux states with a very high barrier condition (ensuring the freezing of the state, fig.2a); then the barrier is reduced for a time interval Δt in order to have coherent oscillations (fig.2b); finally the high barrier condition is restored (fig.2c), freezing in this way the final flux state (that is the population in the two minima). This final state can

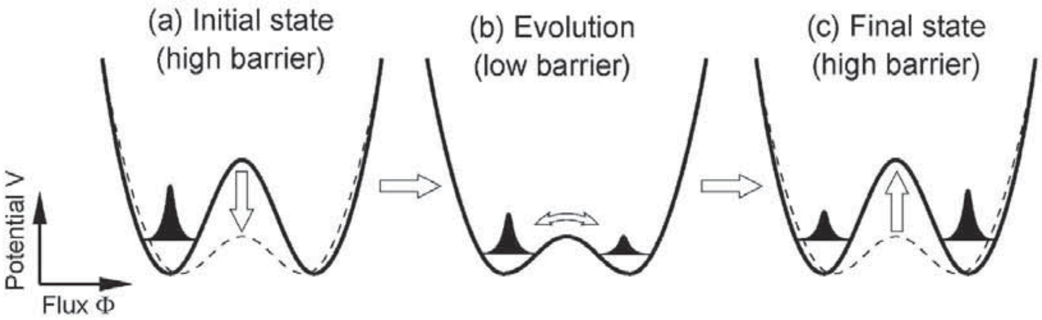

Figure 2: Potential of the double SQUID (double well symmetric case), and manipulation of its state based on the barrier reduction.

be read out by a coupled SQUID magnetometer (for example a dc SQUID) [3, 10].

In 1994, the starting year of the MQC Experiment in Rome, quantum computing had a sudden acceleration. In 80's Richard Feynman speculated on the possibility to use quantum mechanical principles in order to improve computing capabilities. This idea was subject to theoretical investigation, but it remained just an academic question till 1994, when Peter Shor demonstrated the effective potentiality of an hypothetic quantum computer in overcoming the limitations of classical computing [11]. From that moment on, the main question became how to build a real quantum computer and different ideas arose during the next years. Among the most promising ones there was the use of superconducting devices based on the Josephson Effect [12]. This is due to two main reasons: the intrinsic quantum nature of such systems and the possibility to integrate huge systems thanks to microelectronics technology. For these reasons the interest on the MQC Experiment, initially only speculative and concerning fundamental physics, became also practical and began to involve increasing resources and groups.

During the MQC experiment different generations of superconducting devices were designed, fabricated and tested first at 4.2 K and then down to 30 mK thanks to a dilution refrigerator. In the same time it has been developed and perfected the electromagnetic shielding and filtering necessary in order to insulate the system from noise, one of the hardest tasks in this kind of research activity. This allowed first to rediscover fundamental macroscopic quantum effects such as Macroscopic Quantum Tunnelling, Energy Level Quantization and Resonant activation between levels, but in the more complex study of the quantum coherence a great obstacle was encountered. The environment around a quantum system acts as an observer destroying the quantum coherence in a time depending on

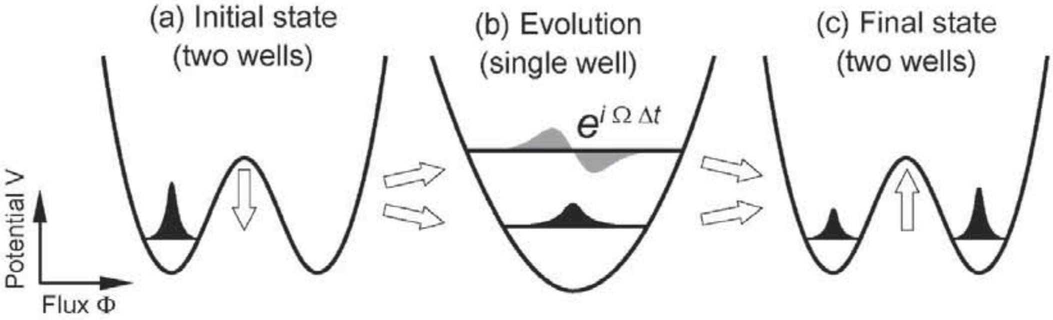

Figure 3: Manipulation with the complete removal of the barrier.

noise intensity and on couplings. Superconducting systems pay their advantages related to flexibility and integrablility with a drawback: they are very sensitive to noise and decoherence and require a very special attention to the insulation from the environment. In our specific case, the oscillation frequency in the double SQUID depends exponentially on the barrier height and so on the control fluxes. Therefore the effect of the unavoidable noise is exponentially amplified and makes impossible to detect coherent oscillations. The solution to this problem was found after many efforts and is based on a complete rethinking of the manipulation protocol. In the more recent form, we consider a manipulation starting again from a flux state frozen in the high-barrier condition (fig.3a), but now the barrier is completely removed arriving to a single-well condition, maintained for a time Δt (fig.3b), after which the system returns back to the high-barrier condition (fig.3c) and the flux state is measured [13, 14, 15].
In this way the system spends only a very short time in the low-barrier condition, where decoherence is strong. The fast (non adiabatic) transition from the double-well to the single-well condition populates equally only the first two energy levels of the system, with an initial phase depending on the initial flux state. During the single-well condition the relative phase evolves with a frequency given by the level spacing. The fast back-transition to the double-well condition causes an inverse modification that projects the new phase into a new superposition of flux states. In the experiment the sequence of preparation - manipulation - readout is repeated many times (1000 - 10000) in order to evaluate the final population in the left well, and this can be repeated for different pulse durations Δt in order to plot the oscillation of the population (fig.4).

The results obtained until now are particularly interesting from a theoretical point of view since they involve and mix together different quantum aspects such as partial Landau-Zener transitions, free coherent oscillations and interferometry of

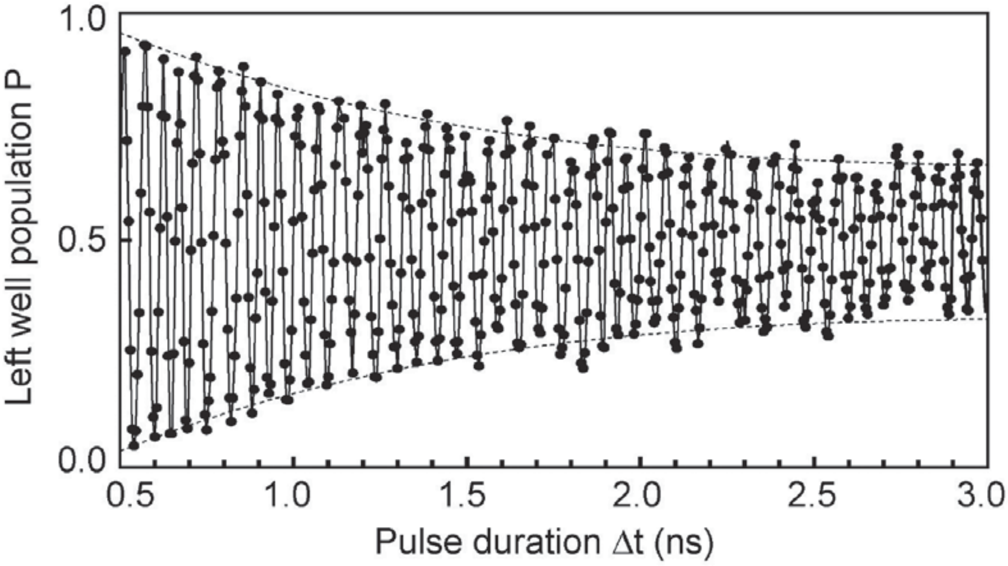

Figure 4: An example of coherent oscillations observed at 30 mK.

macroscopic quantum states, and anomalous decoherence mechanisms [16]. They are also important for quantum computing applications: in fact this scheme is very fast with respect to other more conventional manipulating schemes based on microwave pulses. For example we were able to obtain oscillations with frequencies up to 70 GHz, while for the other schemes the frequency is always below 1 GHz. This gives a great advantage from the point of view of decoherence: the main problem for a real quantum computer concerns the capability to have a sufficient number of quantum operations before decoherence destroys the quantum state (from 1000 to 10000 operations). This can be achieved by increasing the coherence time, but also by increasing the number of operations within this time, as in our case.

The actual main limit is related to the rapidity of controls: it is particularly difficult to apply well-shaped and weakly-distorted pulses with rise-times below 100 ps (as required from the manipulation), starting from room-temperature electronics through the necessary filtering stages at different temperatures, and down to the device at 30 mK. Great efforts of engineering nature are now required in order to further improve the fast manipulation scheme and to make it adequate for a practical implementation.

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