(Mini)lecture 4B

Superconducting qubits:current status and outlook

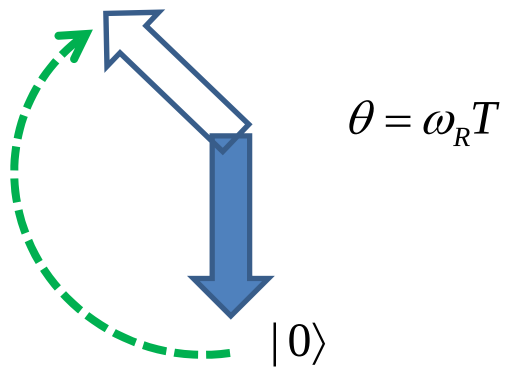
1.Experimental Parameters

Typically,the superconducting devices being explored for their potential as qubits are made using e-beam lithography.The bulk metals involved are usually Al $(T_C \sim 1.3K, so \Delta \sim 2K)$ or Nb $(T_C \sim 9K, \Delta \sim 16K)$ The Josephson junctions are usually Al or Nb oxide.Typical dimensions range from a few microns up to ~150 microns (in the SUNY flux-qubit experiment).The value of the Josephson energy $E_J \equiv I_C \Phi_0 / 2\pi$ tends to be ~1K,corresponding to a critical current of order 50nA;the Coulomb energy $E_C \equiv (2e)^2 / 2C$ is comparable to or smaller than this for charge qubits (corresponding to a capacitance of the order of a few femtoF) ,but is usually considerably larger than this for flux-mode devices.(Note that the « quasiclassicality » parameter λ introduced in lecture 3B is up to a constant of order unity equal to $(E_C / E_J)^{1/2}$). Typical energy level splittings (Larmor frequencies) are in the range 3-15 GHz (0.2-1 K) The experiments are usually done at temperatures of the order of 25mK or below.

2.Measurements:The simplest types of measurement are spectroscopic;one simply varies the oscillation frequency of the (ac part of) the relevant control parameter $(V_g, \Phi_{ext}, I_{ext} \ldots)$ and looks at which value(s) of the frequency the response is resonant.In principle such experiments give information on both the energy splittings of the system in question and the phase relaxation time T_2 of the excited levels . However,this is generally not thought to be a particularly reliable way of measuring T_2 .Both the earliest experiments on SQUIDs and several more recent experiments on coupled qubits are of this type.

What is measured ?(cont.)

A more sophisticated type of measurement is of the Rabi-oscillation type.In NMR language this involves starting (say) in the state |0>,then applying a « field « in the x-direction at the Larmor frequency so as to drive the « spin » through large angles over the Bloch sphere,and then checking where ît has got to. by a measurement of $<\sigma_z>(T)$.In a perfectly undamped System this expectation value would be exactly sinusoidal as a function of T:

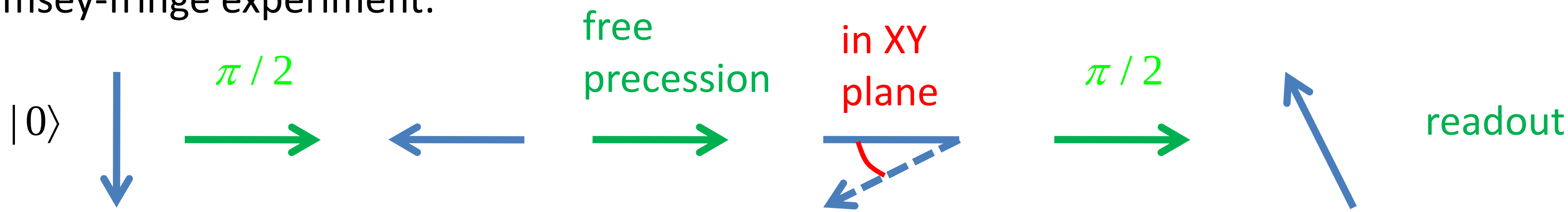


$<\sigma_z>(T) = -\cos(\omega_R T), \omega_R \equiv$ Rabi frequency ($\propto$ ampl.of ac field).

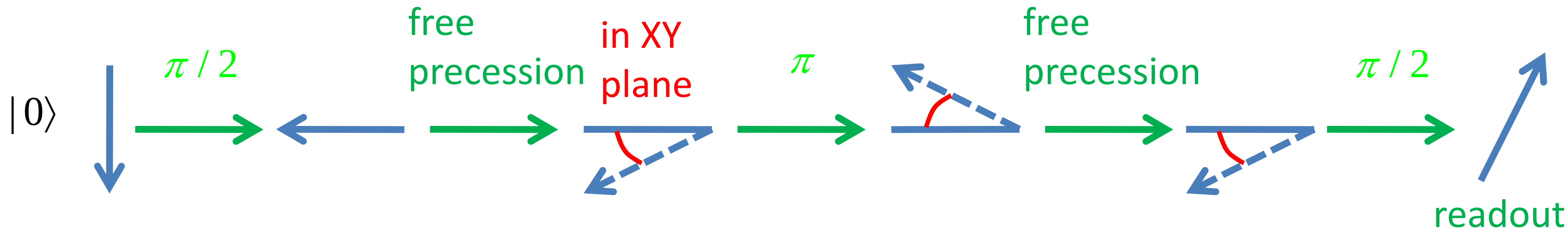
In real life the expectation value has a nonzero decay envelope superimposed on the sinusoidal oscillation, and this rate of decay is the invesre of the energy relaxation time T_1 .Thus Rabi-oscillation experiments are a good way to measure T_1 ,but they cannot tell us about the more important phase relaxation time T_2 .

To measure T_2 the standard technique is a Ramsey-fringe experiment.In NMR language this is essentially a free-precession experiment:one again starts with the state |0>,but now puts on an intense resonant pulse (« $\pi/2$ pulse «) so as to rotate the « spin » into the xy-plane. Next,one turns off the x-field and allows the spin to precess freely for a period T.Finally, one applies a second $\pi/2$ pulse,carefully synchronized with the first,and immediatly following it measures $<\sigma_z>$ .Again,for a totally undamped system we should get pure sinusoidal oscillations as a function of the dealy time T,but now the obserevd decay envelope measures T_2 rather than T_1 .One can get rid of the effects of low-frequency noise by using a « spin-echo » technique.

Ramsey-fringe experiment:



Spin-echo experiment:



Results:values of both T_1 and T_2 now a few microseconds,but more importantly, the « figure of merit » $Q_\phi \equiv \omega_0 T_2$ is as large as 25,00 in the « quantronium » experiments (1).

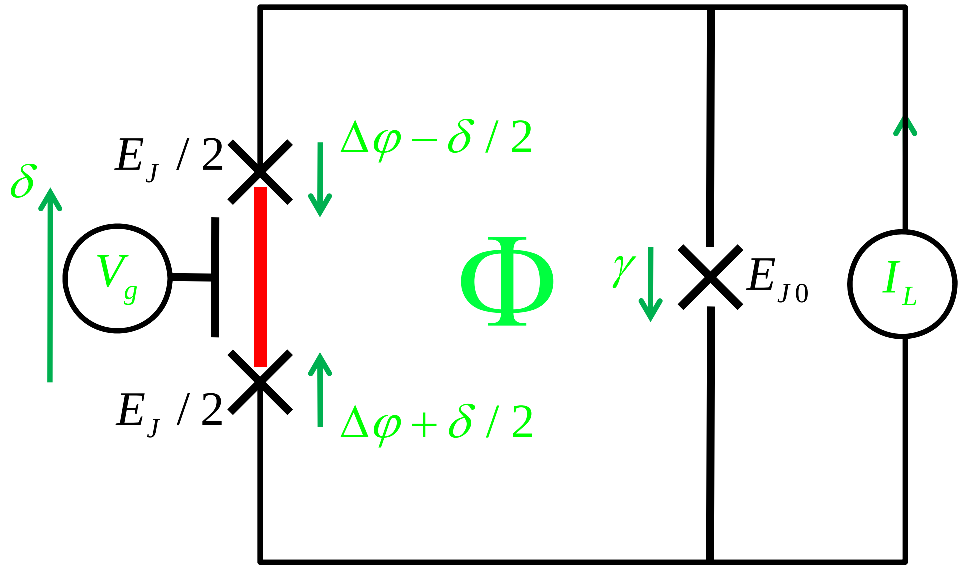
Readout:

Fidelity as high as ~90% obtained in experiments on single charge qubits (2)
Fidelities of ~60% obtained using a CBA (cavity bifurcation amplifier) on quantronium (3)

(1)Vion et al.,Science 296,886 (2002)
(2)O.Astafiev et al.,PR B 69,180507 (2004)
(3)M.Metcalfe et al.,PR B 76,174516 (2007)

A hybrid device:quantronium*

In a standard charge qubit,there is a tension between the avoidance of decoherence and efficiency of readout:The decoherence against charge noise is minimized at the « crossing » point,but precisely at that point the number degree of freedom cannot be used to read out the state!The same applies to the flux qubit,mutatis mutandis.Of course, one can shift away from the crossing point to make the measuerment,but ideally one would like not to have to mess around with the qubit itself.



The « quantronium » design solves this problem by adjusting,between the qubit operation and the readout,not the qubit Itself but a « distant » element of the circuit.With the notation shown in the figure,the Hamiltonian of the qubit (the red area) is

$$H = E_C(\Delta N - \Delta N_g)^2 - E_J\cos(\delta/2)\cos\Delta\phi, [\Delta N, \Delta\phi] = i$$

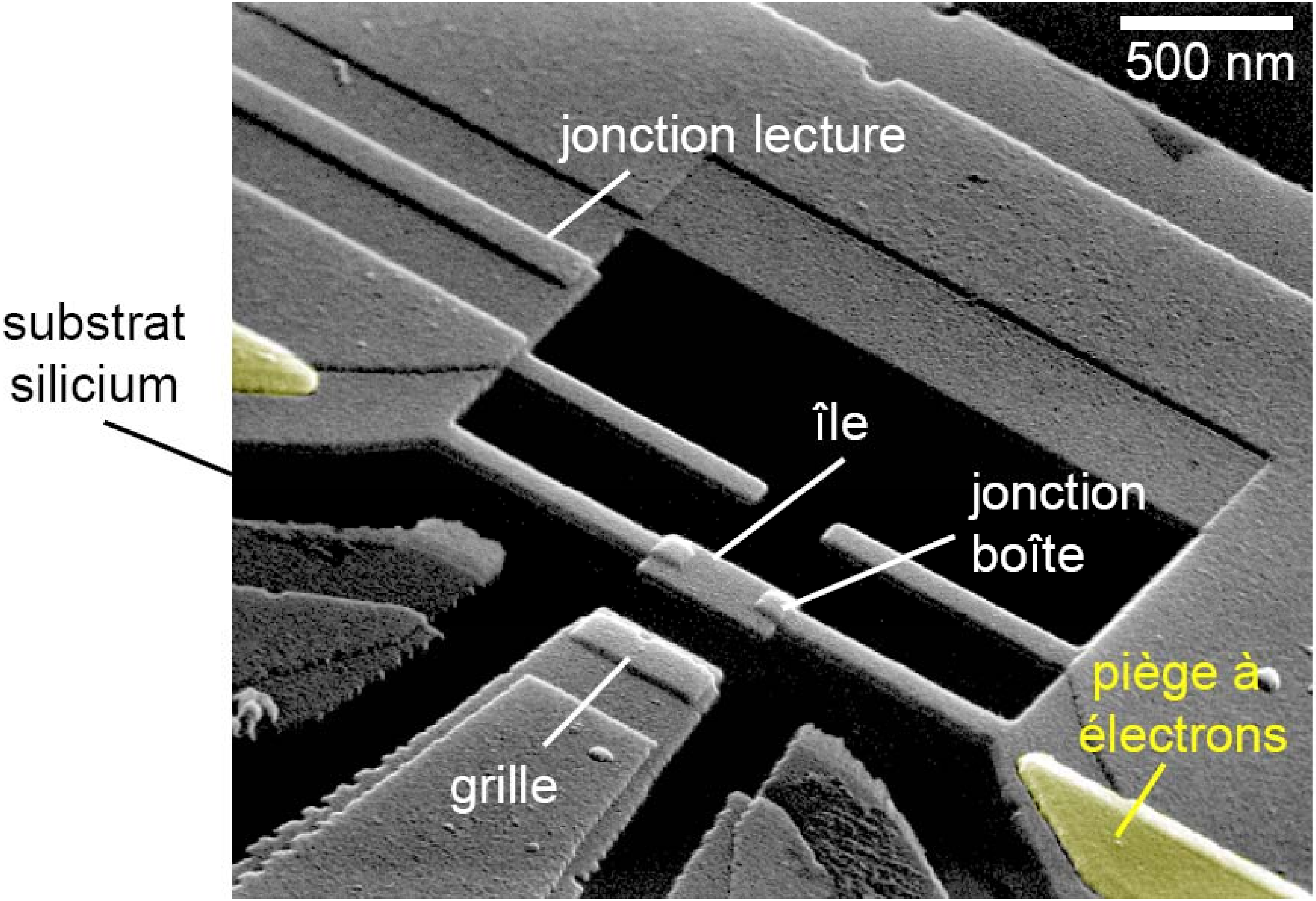
(where ΔN_g is a shorthand for the effects of the gat e voltage),and crucially,the total current through (not into!) the qubit is

$$I_t = (2\pi/\Phi_0)(E_J/2)\sin(\delta/2)\cos\Delta\phi[\equiv(2\pi/\Phi_0)(\partial H/\partial\Delta\phi)]$$

The energy of the « large » junction on the right of the circuit is $E_{J0}\cos\gamma, E_{J0} >> E_J$ .Furthermore,the phases δ and $\gamma = 0$ are related to the flux Φ applied through the circuit by the usual « SQUID » relation

$$\delta = \gamma + 2\pi\Phi/\Phi_0$$

NANO CIRCUIT (1 QUBIT)



The point of the quantronium setup is that one conducts the actual qubit operations with the bias current I_b switched off and $\Phi = 0$ .It is then obvoius from the symmetry of the situation that no current flows across the « large » juntion,so that the phase drops γ and δ (which may be treated as classical quantities for the purposes of the argument) are both zero,and the qubit behaves like a simple charge qubit (and can be manipulated via the gate voltage).There is no current through the qubit (as distinct from into it).Note in particular that if the bias N_g is ½ (so that one is at the « crossing point »),then the system is insensitive to charge noise (i.e.unwanted fluctuations in V_g) to first order.Since $\delta = 0$,the first derivative $\partial H / \partial \delta = 0$ and it is also insensitive to fluctuations in Φ (hence in δ) to first order (« sweet spot »). However,at the end of the day one would like to read out the state in the energy representation at this point.To do so one switches on a value of the bias current just below the critical current of the « large « junction. As this effectively shunts the qubit,the bias current overwhelmoingly goes through it and produces a nonzero value of γ ,hence of δ.Now the crucial point is that the two energy eigenstates have energies $\pm E_J (\cos \delta / 2)$,and thus carry opposite currents $\propto \partial H / \partial \delta = \pm E_J (\sin \delta / 2)$

The relevant current then adds to,or subtracts from,the current through the large junction, triggering it or not into the voltage state depending on the value of the qubit σ_z .Thus the readout is effecively decoupled from the qubit operation.

Entanglement,performance of quantum gates etc.:

A number of spectroscopic experiments on 2-and even 3-qubit systems(4) are consistent with entangled states having been created,but there are (to my knowledge) no « Bell's theorem » results as yet.

An experiment(5) by the Delft group has performed 4 different CNOT gates on two flux qubits.

A primitive adiabatic quantum computation has been carried out by the Jena group (6) using 4 flux qubits.

Problems

All the conditions for successful achievement of quantum computation have now been individually met in at least one superconducting qubit system.The major problem would appear to lie in getting them all simultaneously satisfied in one or more group of such systems.

(4)E.g.Xu et al.,PRL 94,027003(2005);Niskanen et al.,PR B 74,220503 (2006)
(5)Plantenberg et al.,Nature 447,836 (2007)
(6)Van der Ploeg et al.,IEEE Transactions on Applied Superconductivity 17,113 (2007)