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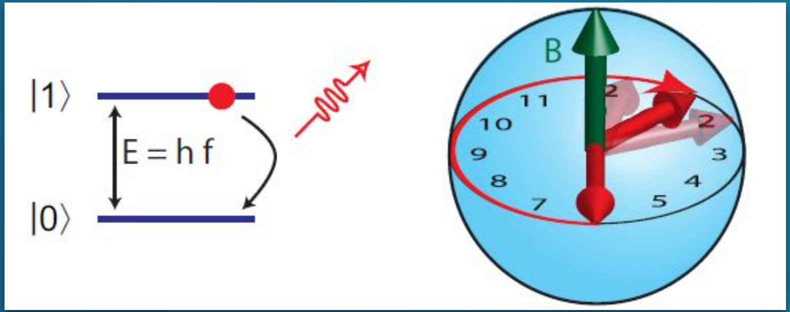
Fermilab

Qubits and atoms

- A qubit consists of two quantum states from any quantum system (e.g., atoms, superconducting circuits) [1]
  - Controllable
  - Coherent
  - Can be in a *superposition of states*



(Right) Frequency of phase o f precession depends on energy gap $\Delta E = hf$ [1]

“In order to prevent decoherence, the elements of a quantum computer must be **isolated from noise**, and yet **strongly coupled** to each other, all the while being controlled by the classical experimenter.” [1]

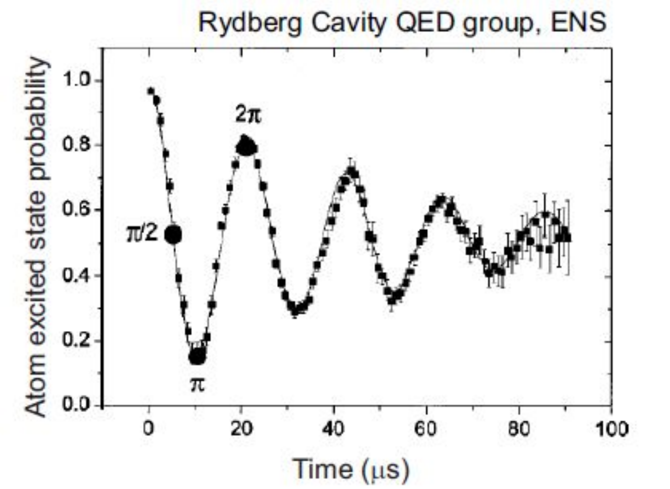
Coupling

- When two systems are **coupled**, a change in one leads to a change in the other
  - When an atom and an electromagnetic wave are coupled, an emission/absorption of a photon and a change in the atom's energy level occur simultaneously
- In a strong coupling regime, the rate at which an atom emits radiation into the waveguide/cavity is substantially greater than the decoherence rate of the atom [2]

Cavity quantum electrodynamics (QED) can help achieve the strong coupling limit

Cavity Quantum Electrodynamics (QED)

- Cavity QED aids the study of light-matter interactions
  - e.g., "an atom modeled as a two-level system coupled to a harmonic oscillator, whose excitations are photons" [1]
- Inside a cavity, the photon is reflected a significantly large amount [3], leading to increased interactions
  - If the atom and photon are resonant and the cavity is not leaky, the strong coupling limit can be reached [1] → coherence → **vacuum Rabi oscillation**



Principles of atomic physics can be used to minimize decoherence in superconducting circuits (Schuster, 2007)

We will use superconducting circuits to study otherwise impossible areas in natural atomic systems

Jaynes-Cummings Hamiltonian

$$H_{JC} = \boxed{\hbar\omega_r}(a^\dagger a + 1/2) + \boxed{\hbar\frac{\omega_a}{2}}\sigma_z + \hbar\boxed{g}(\boxed{a^\dagger\sigma^-} + \boxed{a\sigma^+})$$

- Describes behavior of strongly coupled system
  - energy of a photon
  - transition energy of atom
  - dipole interaction
  - rate of absorption/emission of photon from/to field
- In competition with incoherent phenomena
  - photon decay rate, κ
  - atom decay rate, $\gamma_\perp$
  - finite lifetime of atom, $T_{transit}$
- Strong coupling limit: $g > \kappa, \gamma_\perp, 1/T_{transit}$

References

[1] Schuster, D. I. (2007). *Circuit quantum electrodynamics*. Yale University.

[2] Shen, J. T., & Fan, S. (2005). Coherent single photon transport in a one-dimensional waveguide coupled with superconducting quantum bits. *Physical review letters, 95*(21), 213001.

[3] Vahala, K. J. (2003). Optical microcavities. *Nature, 424*(6950), 839-846.