Lecture 39

Recap -

Spontaneous emission: excited states have finite lifetimes, eventually make spontaneous transmission to ground state

Adiabatic approximation: if H changes slowly enough, system stays in same state while state itself changes.

Rest of the course -

no more hard calculations, say something about what QM means.

Basic question: what exactly is a wavefunction?

Can't observe it directly, behaves in some strange ways.

Today focus on one strange thing: <u>measurement</u>

Suppose we measure something about a particle in state ψ

To be concrete, let's measure energy.

QM says: to predict results, first write ψ as sum of eigenstates of energy operator (H)

$$\psi = \sum_n c_n \psi_n \qquad \text{with } H\psi_n = E_n \psi_n$$

Then measurement gives result E_n with prob $|c_n|^2$

<u>Also</u>, after measurement, system is in state ψ_n

Say that wave function "collapses" to ψ_n

Clear enough, and agrees well with experiments.

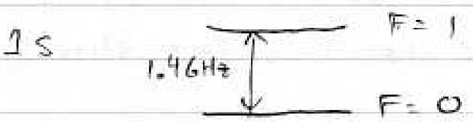
But it is kind of strange.

Evolution of Ψ normally governed by Schr. Eqn,
but Schr. Eqn. doesn't have "collapse" in it.

- Seems inelegant to need two separate types of evolution
- Also, what constitutes a measurement? When exactly do we need to impose this "collapse"?

To get a better idea, consider a measurement example.

Recall hydrogen atom has two ground states due to hyperfine effect



Upper state does decay via spontaneous emission, but lifetime is ~ 40,000 years.
- stable for our purposes

Can prepare an atom in a superposition of Ψ_0 & Ψ_1 by applying B-field oscillating at 1.4 GHz

(Need B, not E, because we're affecting spin instead of charge.)

If we start out in Ψ_0, and apply resonant field $\Delta = 0$ have

$$c_1(t) = -i \sin \frac{\Omega t}{2} \qquad \Omega \propto B$$

In particular, apply for time $t_1 = \frac{2}{\Omega} \cdot \frac{\pi}{4}$

After pulse, $\Psi(t) = \frac{1}{\sqrt{2}}(\Psi_0 - i\Psi_1)$

Now, can measure state by applying laser tuned between F=1 state and 2p excited state.

Set laser strength & duration to drive transition with 100% probability

Then wait several ns. If atom in 2p state it will decay, emitting a photon.

So if we detect photon, know atom was in F=1 state. Furthermore, if we make laser with correct polarization, we can be sure 2p state decayed back to F=1 state

So if we detect photon, know atom is in ψ_1, if no photon, know atom in ψ_0

That is our measurement.

Question is, what makes it a measurement?

Some possible answers:

A: Fact that I, a conscious being, learned the state of the system. Important part is the observer.

B: Fact that the state of my detector changed depending on the state of the atom. Important part is interaction with a macroscopic object.

C: Fact that atom scattered a photon at all. Important part is interaction with anything.

All of these have some merit, but also some problems:

A: Does that mean the universe would behave totally differently if humans weren't around?

B: How big does something have to be to count as macroscopic?

C: But photons are quantum entities. Shouldn't the Schr. eqn handle this by itself?

We can imagine an experiment to resolve these options.

Sequence:

I Prepare atom in ψ_0

P1 Apply B-field pulse $\psi \to \frac{1}{\sqrt{2}}(\psi_0 - i\psi_1)$

M1 Attempt measurement in various ways

P2 Apply B-field again

M2 Measure again in straightforward way.

Two possibilities for M2:

- If M1 is not a successful measurement, then ψ remains $\frac{1}{\sqrt{2}}(\psi_0 - i\psi_1)$

  Then P2 completes transition, $\psi \to \psi_1$

  and M2 gives result ψ_1 every time

- If M1 <u>is</u> a measurement, then ψ is either ψ_0 or ψ_1

If $\psi = \psi_0$, then P2 drives $\psi \to \frac{1}{\sqrt{2}}(\psi_0 - i\psi_1)$

If $\psi = \psi_1$, then P2 drives $\psi \to \frac{1}{\sqrt{2}}(\psi_1 - i\psi_0)$

Either way, M2 gives ψ_0 + ψ_1 both with 50% probability.

So repeat sequence many times and see what M2 gives.

First experiment: Make M1 as described above

Then see M2 vary, as expected.

Second experiment: Make M1 as described, but don't watch detector.

See M2 vary. Seems to rule out A.

Third experiment: Apply laser pulse during M1, but remove detector entirely.

See M2 vary. Seems to rule out B

Fourth experiment: Don't apply laser during M1.

See M2 gives ψ_1 every time, as expected.

So this would seem to mean that C is the answer. But then why doesn't Schr. eqn work here?

Compare, if we don't apply laser. Then field state remains ϕ_0

After P2, have $\Psi = \frac{1}{\sqrt{2}}\left[\frac{1}{\sqrt{2}}(\psi_0 - i\psi_1) - i\,\frac{1}{\sqrt{2}}(\psi_1 - i\psi_0)\right]\phi_0$

$$= \frac{1}{2}\left[\psi_0 - i\psi_1 - i\psi_1 - \psi_0\right]\phi_0$$

$$= -i\psi_1\,\phi_0$$

Get ψ_1 every time, as 4^{th} experiment showed.

So it turns out that "measurements" can be explained without collapsing wave function after all.

Important part is really that state of atom ψ becomes correlated with state of field ϕ

Word for this kind of quantum correlation is "entanglement."

We'll talk more about entanglement in next few days.