D. How wrong (right) was Bohr?

	Bohr	QM
• Stationary states	ad hoc	Energy eigenstates, i.e. those ψ $\hat{H}\psi = E\psi$
• Where is the electron?	Orbits at $r_n = n^2 a_0$	$\lvert\psi\rvert^2 d\tau$ (Born) $P(r)$ {1s peaks at a_0; 2p peaks at $4a_0$; 3d peaks at $9a_0$}
• Angular momentum	$L = n\hbar$ Bohr's ad hoc rule [$n = 1, 2, 3, \ldots$]	Bohr was wrong quantitatively! $L = \sqrt{l(l+1)}\,\hbar$ ($\sqrt{l(l+1)}$: not an integer)

- Bohr was rather lucky to get his model to work!
- Bohr did have the insight of L being quantized

Bohr said: Atomic spectrum comes from transitions between allowed energy levels (the E_n's) of the atom

$$\nu = \frac{E_m - E_n}{h} \quad \text{for transition from } m \text{ to } n$$

- Should realize that Bohr first imposed the condition that stationary states would not lose energy as expected of an orbiting electron (classical electrodynamics)
- Then Bohr said there could be transitions (giving out $h\nu$) between the stationary states!
- That's fine for an ad hoc model and he got the right ν's as observed in hydrogen spectrum.

How about QM?

- Apparently, a conceptual problem? $\hat{H}_{H\text{-atom}}\psi_{n\ell m_\ell} = E_n \psi_{n\ell m_\ell}$
  - Energy eigenstates have infinite lifetime
    - Meaning: System in $\psi_{n\ell m_\ell}$ at time "0", it will stay there forever!
      [recall: how energy eigenstate evolves]

"How can a transition between eigenstates of $\hat{H}_{H\text{-atom}}$ occur?"

"How does an excited atom deexcite to a lower energy state and emit a photon?"

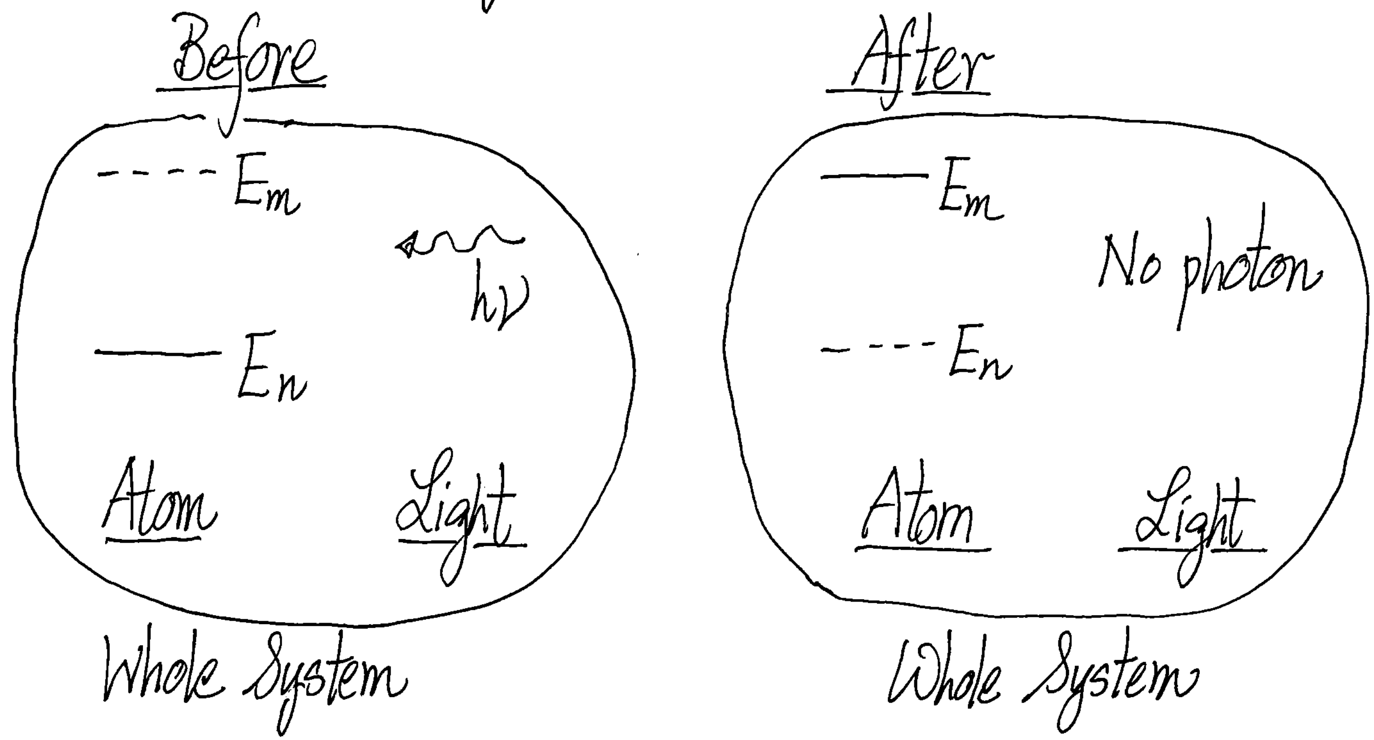
Is there something wrong with QM?

[Preview: No problem. QM is correct!]

Think like a physicist!

- If $\hat{H}_{H\text{-atom}}$ is all that is here, [meaning: an isolated atom] [isolated from everything including vacuum], then eigenstate of $\hat{H}_{H\text{-atom}}$ will <u>not</u> make transitions
- But we <u>can't</u> have isolated atom.
- Transition ⇒ light is involved (absorbed OR emitted)

Absorption



$\hat{H}_{H\text{-atom}}$ is <u>NOT</u> the Whole System

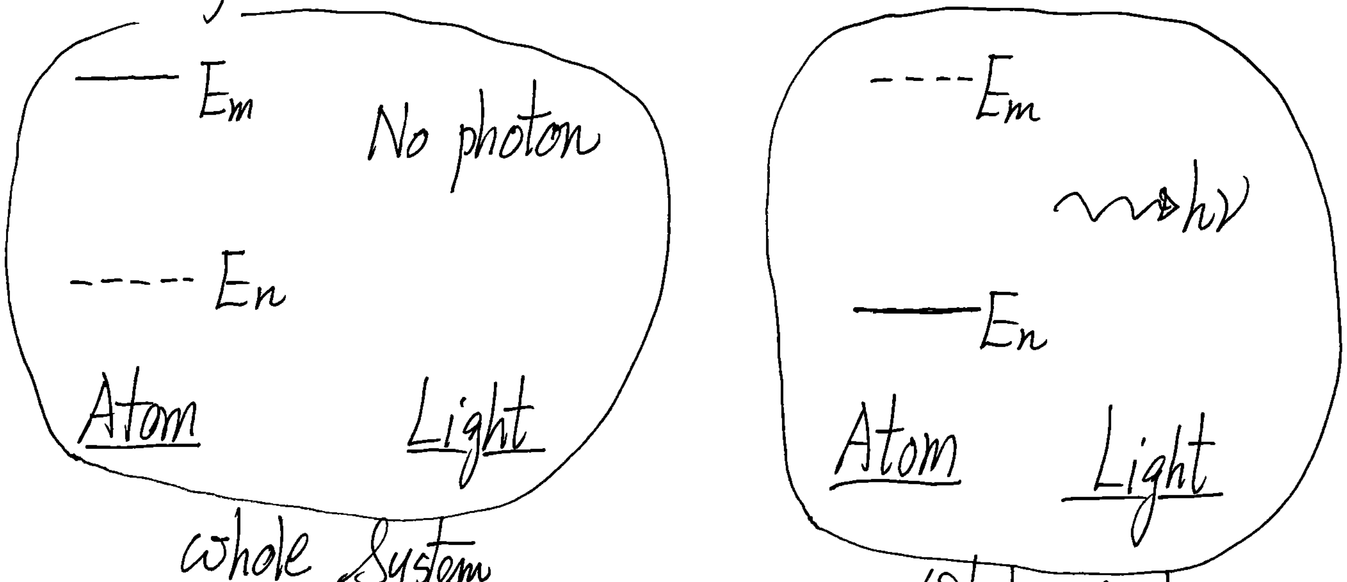
The <u>Whole System</u> is Matter, Light, and Matter-Light Interaction

$$\hat{H}_{whole} = \underbrace{\hat{H}_{H\text{-}atom}}_{\text{isolated atom [what we solved]}} + \hat{H}_{photon} + \hat{H}_{interaction}$$

- No wonder ψ_{atom} is not an eigenstate of $\hat{H}_{whole}$ and transitions can occur.
- $\hat{H}_{interaction}$ causes transitions between $\hat{H}_{H\text{-}atom}$'s eigenstates
- Easier approach: Perturbation Theory
- Formal approach: $\underbrace{\text{QED}}_{\text{quantum electrodynamics}}$
  - $\hat{H}_{photon}$ (quantize EM field)
  - $\hat{H}_{interaction}$ (photon interacts with Matter (Atom))

Emission

Before | **After**



whole System | Whole System

Is "No photon" state really Nothing (Vacuum)?

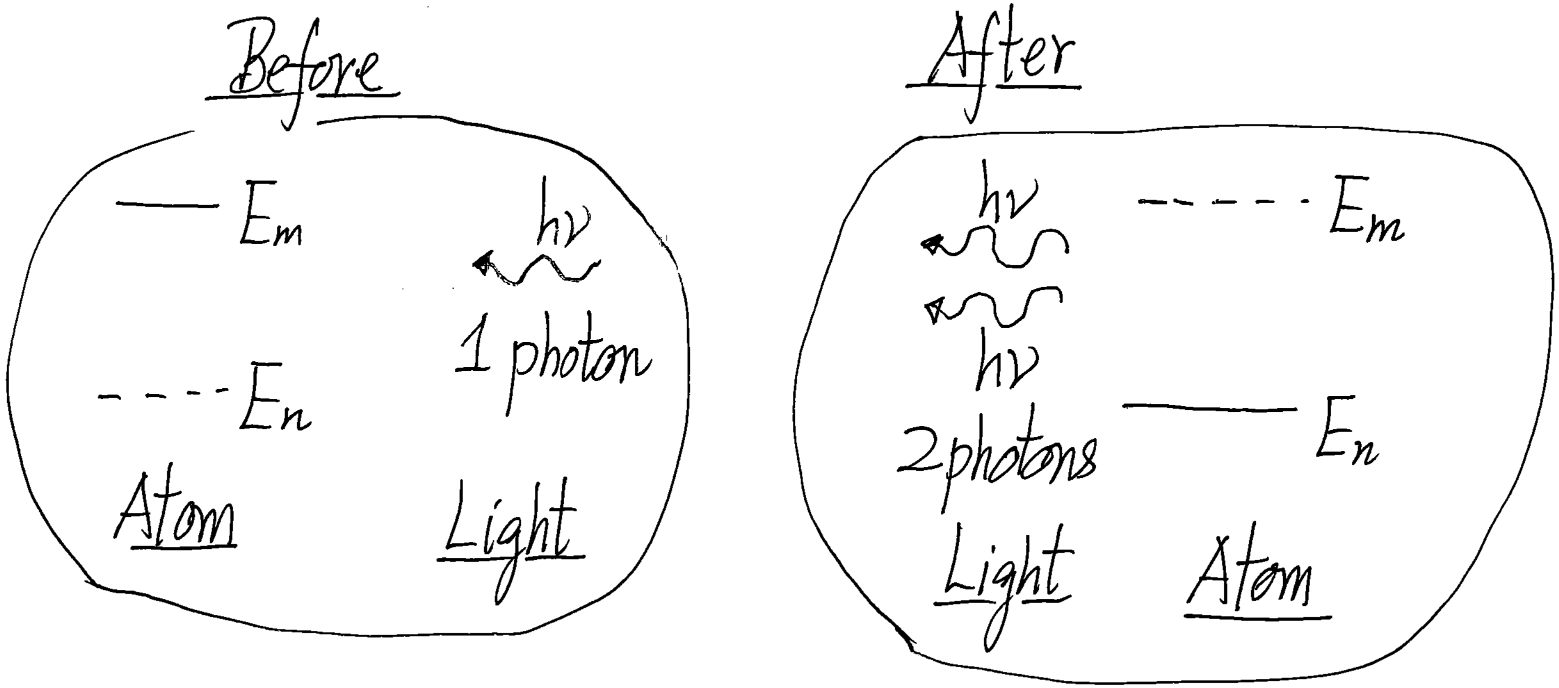
- "No photon" state is Ground state of (Quantized) EM fields

"No photon" state → Vacuum ≠ Nothing!

Ground state of (Quantized) EM fields → like ground state of harmonic oscillator [ground state (zero point) energy]

By-Product (1917 Einstein)

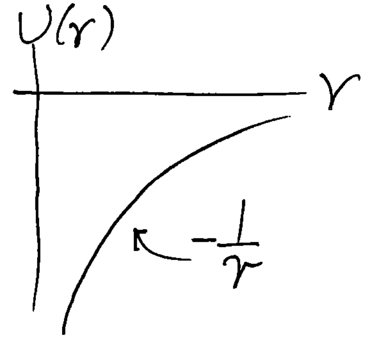
Stimulated Emission



Laser: Light Amplification by Stimulated Emission of Radiation ("EM")

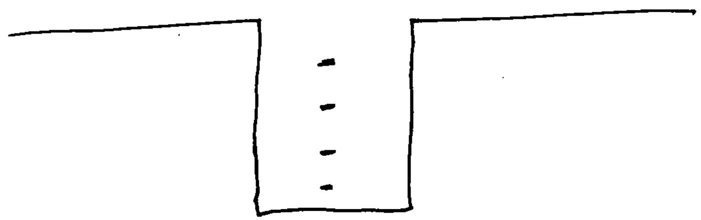
E. "Finite Well" is a good Portable Model of atoms

- Of course, we can move on to solve He, Li, Be, ... atom's TISE
- Inspecting H-atom solutions



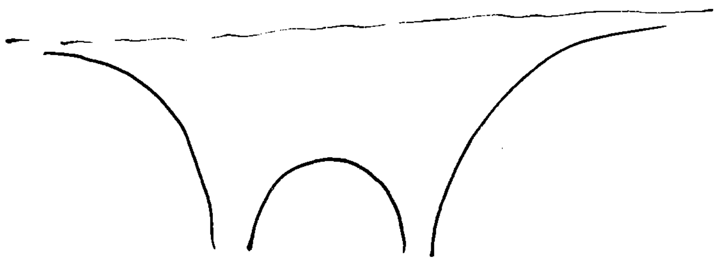
bound states
1s, 2s, 2p, ...
energy increases

- Not too far from

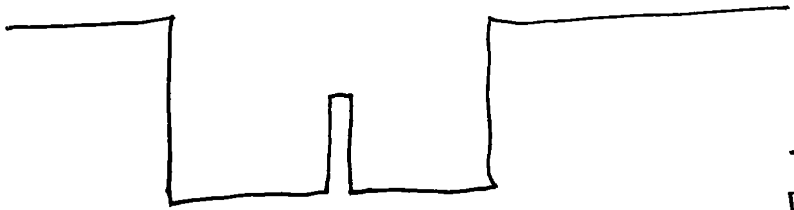


- some bound states
- tails into forbidden region longer for higher energy bound state

H_2 molecule:

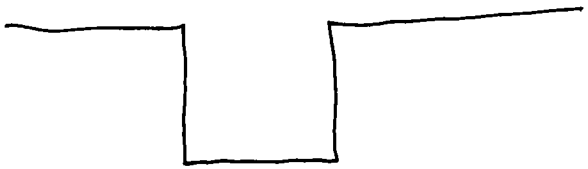


TISE
⇒ molecular states



like a molecular
[easy to visualize]

Take-Home Message



"like an atom"

Summary

- TISE + Boundary Conditions $\Rightarrow$ Hydrogen atomic orbitals + E_n
- $U(r) \sim -\frac{1}{r}$ $\Rightarrow$ $E_{n\ell} = E_n$ only ($\therefore$ higher degeneracy)
- $\psi_{n\ell m_\ell}(r,\theta,\phi) = R_{n\ell}(r) \cdot Y_{\ell m_\ell}(\theta,\phi)$
- Y_{10} (z-direction), Y_{11} and Y_{1-1} combine to give p_x and p_y
- Directional (e.g. p) orbitals are important in forming bonds (molecules)
- QM is the microscope theory of atoms [Bohr's is just a model]
- Considering Atom (Matter) - Light interaction leads to transitions