Title: Quantum Theory - Lecture 220919

Speakers: Dan Wohns

Collection: Quantum Theory (2022-2023)

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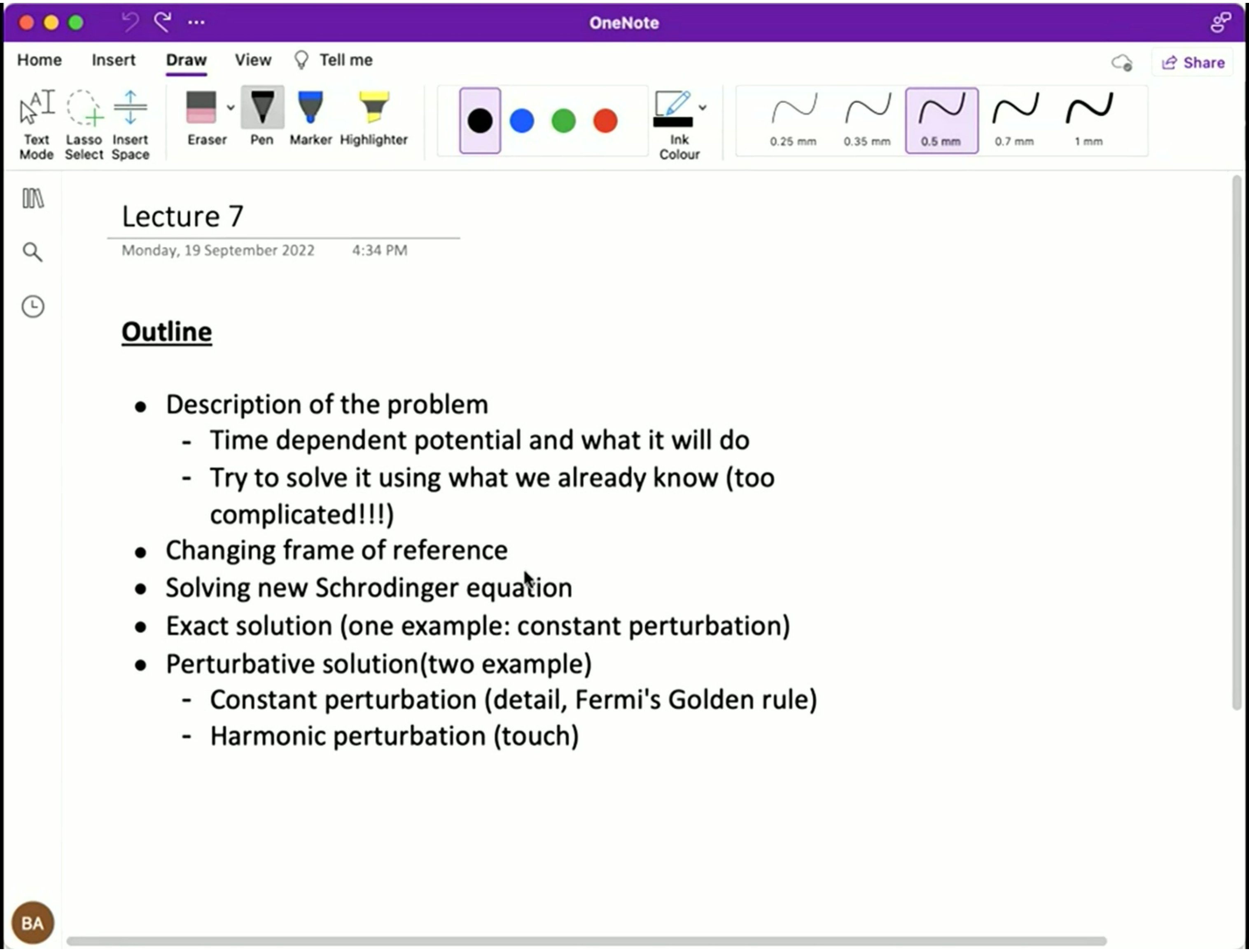


Lecture 7

Monday, 19 September 2022 4:34 PM

Outline

- Description of the problem
  - Time dependent potential and what it will do
  - Try to solve it using what we already know (too complicated!!!)
- Changing frame of reference
- Solving new Schrodinger equation
- Exact solution (one example: constant perturbation)
- Perturbative solution(two example)
  - Constant perturbation (detail, Fermi's Golden rule)
  - Harmonic perturbation (touch)

Goal $H(t) = \underset{\substack{\downarrow \\ \text{can be easily}}}{H_0} + V(t) \longrightarrow$ tricky

$$e^{-iE_nt/\hbar}$$

$$i\hbar \frac{\partial}{\partial t}|\psi(\underline{\underline{t}})\rangle = \underline{H(t)}\,|\psi(t)\rangle$$

$$\underset{\substack{\downarrow \\ \boxed{|n\rangle}}}{H|\psi\rangle} = E|\psi\rangle \qquad E_n$$

$$|\psi(t)\rangle = \sum_n \underline{\underline{c_n}}(t)\,|n\rangle \rightarrow x$$

$$f(x) = \sum c_n |n\rangle$$

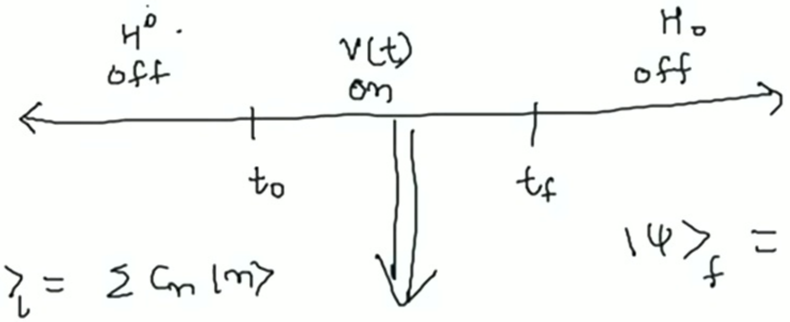
∂t

$$\xrightarrow{V(t)} |\psi(t)\rangle = \sum_n \underline{\underline{C_n(t)}}|n\rangle$$

$$|\psi\rangle = \sum C_n |n\rangle$$

∂t

$$\xrightarrow{V(t)} |\psi(t)\rangle = \sum_n \underline{\underline{C_n(t)}}|n\rangle$$



$$|\psi\rangle_i = \sum C_n |n\rangle$$

$$|\psi\rangle_f = \sum C_n' |n\rangle$$

$$|\psi\rangle = \sum C_n(t) |n$$

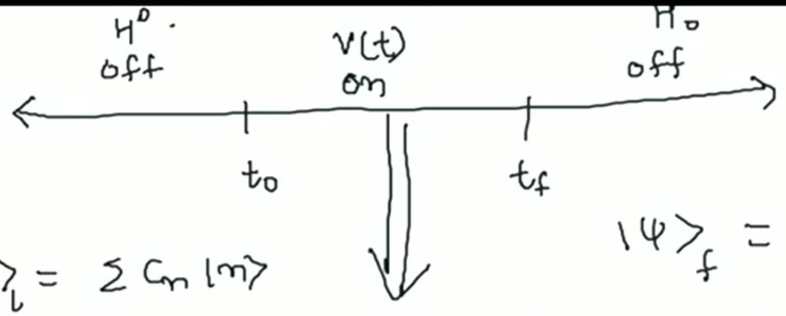
t_0 $\downarrow$ t_f

$|\psi\rangle_i = \sum C_n |n\rangle$

$|\psi\rangle_f = \sum C'_n |n\rangle$

$|\psi\rangle = \sum C_n(t) |n\rangle$

● Rb   5s $|5s\rangle = |5s\rangle + |$



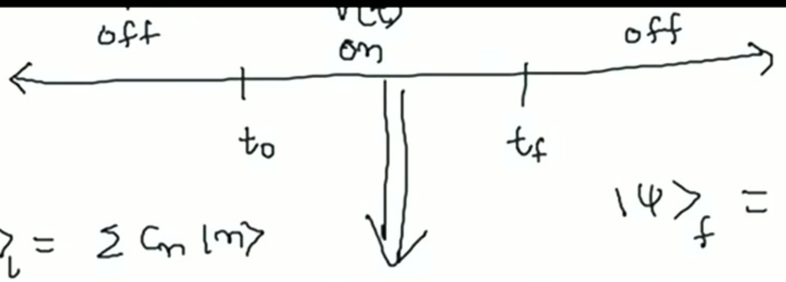
$$|\psi\rangle_i = \sum C_n |n\rangle$$

$$|\psi\rangle_f = \sum C_n' |n\rangle$$

$$|\psi\rangle = \sum C_n(t) |n\rangle$$

● Rb 5s

$$|5s\rangle = \underset{\underset{1}{\Downarrow}}{C_{5s}} |5s\rangle + \underset{\Downarrow}{C} |5p_{1/2}\rangle + ---$$



$|\psi\rangle_i = \sum c_n |n\rangle$

$|\psi\rangle_f = \sum c'_n |n\rangle$

$|\psi\rangle = \sum c_n(t) |n\rangle$

$$i\hbar \frac{\partial}{\partial t} |\psi(t)\rangle = H(t) |\psi(t)\rangle$$

$$|\psi\rangle_i = \sum c_n |n\rangle \quad \Downarrow \quad |\psi\rangle_f = \sum c_n |n\rangle$$

$$|\psi\rangle = \sum c_n(t)\,|n\rangle$$

$$i\hbar \frac{\partial}{\partial t}|\Psi(t)\rangle = H(t)\,|\Psi(t)\rangle$$

$$(H_0+V) \quad (\quad)$$

$$\Uparrow$$

$$H(t') \; H(t'')$$

$$|\Psi(t)\rangle = \sum_n \left(-\frac{i}{\hbar}\right)^n \int_0^{t} dt' \int_0^{t'} \cdots \int_0^{t^{n-1}} dt^n \, \underline{\underline{H(t^n)}} \; |\psi(t_0)\rangle$$

$$\underline{(H_0 + V(t'))}$$

$$|\psi\rangle_i = \sum c_n |n\rangle \quad \Downarrow \quad |\psi\rangle_f = \sum c_n |n\rangle$$

$$|\psi\rangle = \sum c_n(t) |n\rangle$$

$$i\hbar \frac{\partial}{\partial t} |\psi(t)\rangle = H(t) |\psi(t)\rangle$$

$$|\psi(t)\rangle = \sum_n \left(-\frac{i}{\hbar}\right)^n \int_0^t dt' \int_0^{t'} \cdots \int_0^{t^{n-1}} dt^n \, \underline{H(t')} \, \underline{H(t'')} \cdots \underline{H(t^n)} \; \underline{\underline{|\psi(t)\rangle}}$$

$$\underline{H(t')} \downarrow \left(\underline{H_0} + \underline{V(t')}\right)$$

$|\psi\rangle_i = \sum c_n |n\rangle$ $\Downarrow$ $|\psi\rangle_f = \sum c_n |n\rangle$

$$|\psi\rangle = \sum c_n(t)\,|n\rangle$$

$$i\hbar \frac{\partial}{\partial t}|\psi(t)\rangle = H(t)\underline{\underline{|\psi(t)\rangle}}$$

$$|\psi(t)\rangle = \left(\sum_n \left(-\frac{i}{\hbar}\right)^n \int_0^t dt' \int_0^{t'} \cdots \int_0^{t^{n-1}} dt^n \; \underset{\big(H_0+V(t')\big)}{\underset{\downarrow}{\underline{H(t')}}} \; H\underline{(t'')} \cdots H\underline{(t^n)}\right) \underline{\underline{|\psi}}$$

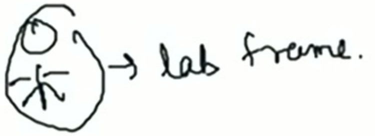
$$i\hbar \frac{\partial}{\partial t}|\Psi(t)\rangle = H(t)\underline{\underline{|\Psi(t)\rangle}}$$

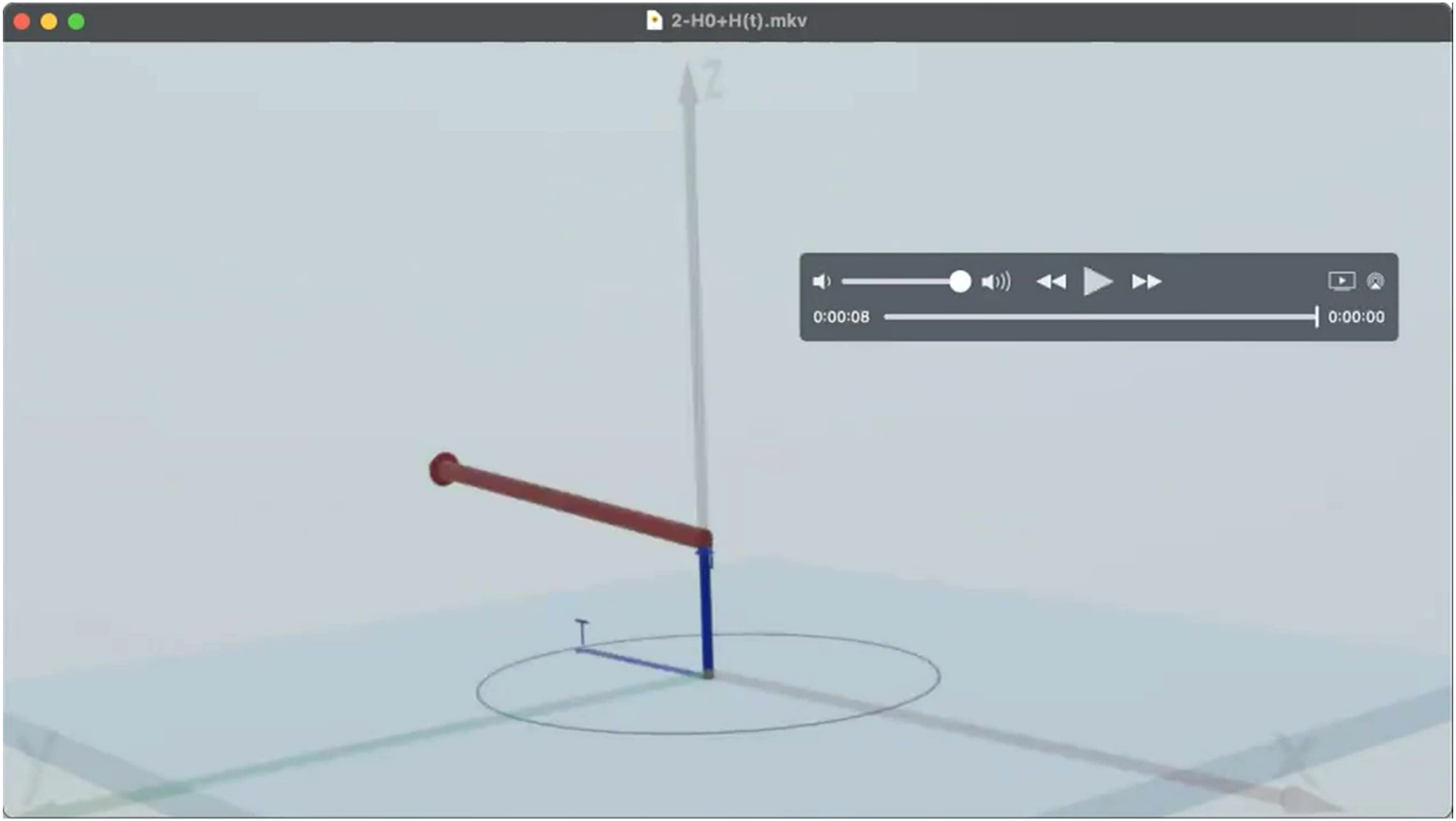
$$|\Psi(t)\rangle = \left(\sum_n \left(-\frac{i}{\hbar}\right)^n \int_0^t dt' \int_0^{t'} - - \int_0^{t^{n-1}} dt^n \; \underset{\underset{\left(\underline{H_0} + \underline{V(t')}\right)}{\downarrow}}{\underline{H(t')}} \; \underline{H(t'')} \; - \cdot \cdot - \; \underline{H(t^n)}\right) \underline{\underline{|\Psi(0}}$$

$$H(t) = \underline{\underline{H_0}} + \underline{\underline{V(t)}}$$

$$n \quad 0 \quad 0 \quad 0 \quad \left(\underline{H}_0 + \underline{V}(t')\right)$$

$$H(t) = \underline{\underline{H_0}} + \underline{\underline{V(t)}}$$




2-H0+H(t).mkv
0:00:08
0:00:00
Z
Y
X

$$i\hbar \frac{\partial}{\partial t}|\psi(t)\rangle_S = \left(H^0 + V(t)\right)|\Psi(t)\rangle_S \qquad U_0^{\dagger}\,|\psi(t_0)\rangle \;\cdot$$

$$|\tilde{\psi}(t)\rangle = R(t)\,|\psi(t)\rangle_S \qquad \Rightarrow \qquad |\psi(t)\rangle_S = R^{\dagger}(t)\,|\tilde{\psi}(t)\rangle$$

$$i\hbar\,|\dot{\tilde{\psi}}(t)\rangle = \underbrace{\left(\dot{R}(t)\,R^{\dagger}(t)\,i\hbar \quad + \quad R(t)\,H(t)\,R^{\dagger}(t)\right)}_{H'(t)}|\tilde{\psi}(t)\rangle$$

$$R(t) = U_0^{\dagger} = e^{iH_0 t/\hbar}$$

$$i\hbar\,|\dot{\tilde{\psi}}(t)\rangle = \Big\{ i\hbar \left[\frac{iH_0}{\hbar}\right] e^{iH_0 t/\hbar} \; e^{-iH_0 t/\hbar} \; +$$

$$i\hbar \frac{\partial}{\partial t}|\psi(t)\rangle_S = \left(H^0 + V(t)\right)|\Psi(t)\rangle_S \qquad U_0^\dagger\, |\Psi(t_0)\rangle$$

$$|\tilde{\psi}(t)\rangle = R(t)\,|\psi(t)\rangle_S \qquad \Rightarrow \qquad |\psi(t)\rangle_S = R^\dagger(t)\,|\tilde{\psi}(t)\rangle$$

$$i\hbar\,|\dot{\tilde{\psi}}(t)\rangle = \underbrace{\left(\dot{R}(t)\,R^\dagger(t)\,i\hbar + R(t)\,H(t)\,R^\dagger(t)\right)}_{H'(t)}|\tilde{\psi}(t)\rangle$$

$$R(t) = U_0^\dagger = e^{iH_0 t/\hbar}$$

$$i\hbar\,|\dot{\tilde{\psi}}(t)\rangle = \left\{\underline{i\hbar\left[\frac{iH_0}{\hbar}\right] e^{iH_0t/\hbar}\, e}^{-iH_0t/\hbar} + \underline{e}^{iH_0t/\hbar}\left[\underline{H}^0 + \underline{V}(t)\right]\underline{e}^{-iH_0t/\hbar}\right) \underset{|\tilde{\psi}(t)\rangle}{}$$

$$i\hbar\,|\dot{\tilde{\psi}}(t)\rangle = \underbrace{e^{iH_0t/\hbar}\,V(t)\,e^{-iH_0t/\hbar}}_{\tilde{V}(t)}\,|\tilde{\psi}(t)\rangle$$

$$|\tilde{\psi}(t)\rangle = e^{-\frac{iH_0t}{\hbar}} |\psi(t)\rangle_s \qquad \underline{|\tilde{\psi}(t)\rangle = e^{-\int\frac{i\tilde{V}(t')dt'}{\hbar}} |\tilde{\psi}(t_0)\rangle}$$

$$\Downarrow$$

$$\tilde{V}(t) = e^{iH_0t/\hbar}\, V(t)\, e^{-iH_0t/\hbar}$$

$$i\hbar |\dot{\tilde{\psi}}(t)\rangle = \tilde{V}(t) |\tilde{\psi}(t)\rangle \quad - (1)$$

$$\boxed{\omega_{mn} = E_m - E_n}$$

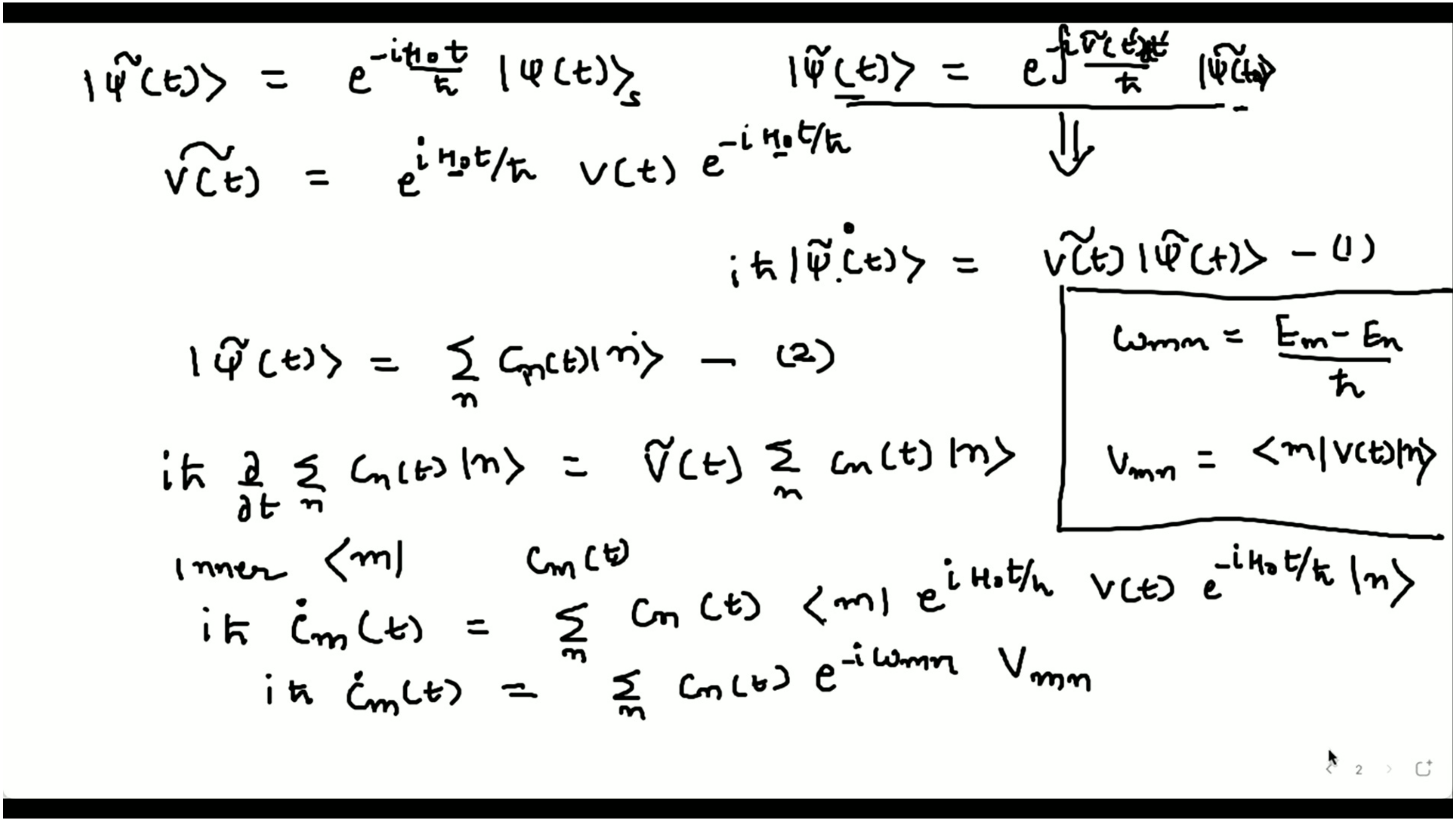
$$|\tilde{\psi}(t)\rangle = \sum_n c_n(t)|n\rangle \quad - \quad (2)$$

$$i\hbar \frac{\partial}{\partial t} \sum_n c_n(t)|n\rangle = \tilde{V}(t) \sum_n c_n(t)|n\rangle$$

inner $\langle m|$ $\quad c_m(t)$

$$i\hbar\, \dot{c}_m(t) = \sum_n c_n(t) \langle m| e^{iH_0t/\hbar}\, V(t)\, e^{-iH_0t/\hbar} |n\rangle$$

$$i\hbar\, \dot{c}_m(t) = \sum_n c_n(t)\, e^{-i\omega_{mn}}\, V_{mn}$$



$$|\tilde{\psi}(t)\rangle = e^{-\frac{iH_0 t}{\hbar}} |\psi(t)\rangle_s \qquad |\tilde{\psi}(t)\rangle = e^{-\int \frac{i\tilde{V}(t')dt'}{\hbar}} |\tilde{\psi}(t_0)\rangle$$

$$\Downarrow$$

$$\tilde{V}(t) = e^{iH_0 t/\hbar} \, V(t) \, e^{-iH_0 t/\hbar}$$

$$i\hbar |\dot{\tilde{\psi}}(t)\rangle = \tilde{V}(t) |\tilde{\psi}(t)\rangle \quad — (1)$$

$$\omega_{mn} = \frac{E_m - E_n}{\hbar}$$

$$V_{mn} = \langle m | V(t) | n \rangle$$

$$|\tilde{\psi}(t)\rangle = \sum_n c_n(t) |n\rangle \quad — (2)$$

$$i\hbar \frac{\partial}{\partial t} \sum_n c_n(t) |n\rangle = \tilde{V}(t) \sum_n c_n(t) |n\rangle$$

inner $\langle m|$ $\quad c_m(t)$

$$i\hbar \, \dot{c}_m(t) = \sum_n c_n(t) \langle m | e^{iH_0 t/\hbar} \, V(t) \, e^{-iH_0 t/\hbar} |n\rangle$$

$$i\hbar \, \dot{c}_m(t) = \sum_n c_n(t) \, e^{-i\omega_{mn}} \, V_{mn}$$

$$|\tilde{\psi}(t)\rangle = e^{-\frac{iH_0 t}{\hbar}}|\psi(t)\rangle_s \qquad \underline{|\tilde{\psi}(t)\rangle = e^{-\int\frac{i\tilde{V}(t)dt'}{\hbar}}|\tilde{\psi}(t_0)\rangle}$$

$$\Downarrow$$

$$\tilde{V}(t) = e^{iH_0 t/\hbar}\, V(t)\, e^{-iH_0 t/\hbar}$$

$$i\hbar|\dot{\tilde{\psi}}(t)\rangle = \tilde{V}(t)|\tilde{\psi}(t)\rangle \quad -(1)$$

$$\omega_{mn} = \frac{E_m - E_n}{\hbar}$$

$$V_{mn} = \langle m|V(t)|n\rangle$$

$$|\tilde{\psi}(t)\rangle = \sum_n C_n(t)|n\rangle \quad - \quad (2)$$

$$i\hbar\frac{\partial}{\partial t}\sum_n C_n(t)|n\rangle = \tilde{V}(t)\sum_n C_n(t)|n\rangle$$

Inner $\langle m|$ $\qquad C_m(t)$

$$i\hbar\,\dot{C}_m(t) = \sum_n C_n(t)\,\langle m|e^{iH_0 t/\hbar}\,V(t)\,e^{-iH_0 t/\hbar}|n\rangle$$

$$i\hbar\,\dot{C}_m(t) = \sum_n C_n(t)\,e^{+i\omega_{mn}}\,V_{mn}$$

< 2 >

$$i\hbar \begin{bmatrix} \dot{c}_1(t) \\ \dot{c}_2(t) \\ \vdots \end{bmatrix} = \begin{bmatrix} V_{11} & V_{12} e^{i\omega_{12} t} & \cdots \\ & V_{22} & \ddots \\ \vdots & & \\ - & - & - \end{bmatrix} \begin{bmatrix} c_1(t) \\ c_2(t) \\ \vdots \end{bmatrix}$$

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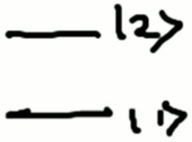
constant perturbation applied to two level problem



$$i\hbar \begin{bmatrix} \dot{c}_1(t) \\ \dot{c}_2(t) \end{bmatrix} = \begin{bmatrix} V_{11} & V_{12}\, e^{i\overset{\rightarrow E_2 - E_1}{\omega_{12}} t} \\ V_{21}\, e^{i\overset{E_2 - E_1}{\overset{\uparrow}{\omega_{\underline{21}}}} t} & V_{22} \end{bmatrix} \begin{bmatrix} c_1(t) \\ c_2(t) \end{bmatrix}$$

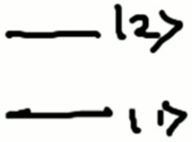
$$i\hbar \; \dot{c}_1(t) =$$

$$i\hbar \begin{bmatrix} \dot{c}_1(t) \\ \dot{c}_2(t) \\ \vdots \end{bmatrix} = \begin{bmatrix} V_{11} & V_{12}\,e^{i\omega_{12}t} & \cdots \\ & V_{22} & \cdots \\ \vdots & & \\ - & - & - \end{bmatrix} \begin{bmatrix} c_1(t) \\ c_2(t) \\ \vdots \end{bmatrix}$$

---

constant pertubation applied to two level problem

$$i\hbar \begin{bmatrix} \dot{c}_1(t) \\ \dot{c}_2(t) \end{bmatrix} = \begin{bmatrix} V_{11} & V_{12}\,e^{i\overset{\nearrow E_2-E_1}{\omega_{12}}t} \\ V_{21}\,e^{i\overset{E_2-E_1}{\overset{\uparrow}{\omega_{\underline{21}}}}t} & V_{22} \end{bmatrix} \begin{bmatrix} c_1(t) \\ c_2(t) \end{bmatrix}$$



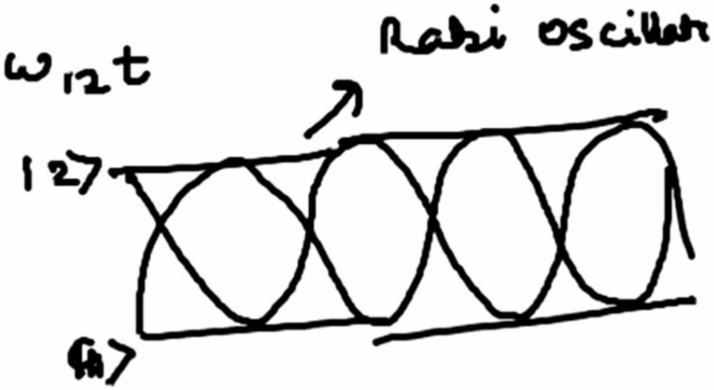
$$i\hbar\ \dot{c}_1(t) = V\ c_2(t)\ e^{i\omega_{12}t}$$

$$i\hbar\ \dot{c}_2(t) = V\ c_1(t)\ e^{-}$$

$$i\hbar\,\dot{c}_1(t) = \overset{\downarrow}{V}\,c_2(t)\,e^{i\omega_{12}t}$$

$$\Rightarrow i\hbar\,\dot{c}_2(t) = V\,c_1(t)\,e^{-i\omega_{12}t}$$

$$\begin{bmatrix} \overset{1}{0} & Ve^{i\omega_{12}t} \\ Ve^{-i\omega_{12}t} & 0 \end{bmatrix}$$



$$\ddot{c}_2(t) + i\omega_{12}\,\dot{c}_2(t) + \frac{V^2}{\hbar^2}\,c_2(t) = 0$$

$c_1(0) = 1 \quad c_2(0) = 0$

$|c_2(t)|^2 \propto \sin^2(\omega_{21}t) \rightarrow$

$|c_1(t)|^2 \propto \cos^2(\omega_{21}t) \rightarrow$

Peturbative solution

$$i\hbar\, \dot{c}_m(t) = \sum_n e^{i\omega_{mn}t} V_{mn}\, c_n(t) \rightarrow$$

$$\underline{c_m}(t) = c_I(0) + \frac{1}{i\hbar} \sum_n \int_0^t dt'\, c_n(0)\, V_{mn}(t')\, e^{i\omega_{mn}t'}$$

$$+ \left(\frac{1}{i\hbar}\right)^2 \sum_m \sum_l \int_0^t dt' \int_0^{t'} dt''\, c_l(t'')\, V_{nl}(t'')\, e^{i\omega_{mn}t''}\, V_{mn}(t')\, e^{i\omega_{mn}t'} + \cdots$$

Peturbative solution

$$i\hbar\,\dot{c}_m(t) = \sum e^{i\omega_{mn}t}\,V_{mn}\,c_n(t) \rightarrow$$

$\langle m|\,\underline{V(t)}\,|n\rangle$

$c_m^1(t)$

$\uparrow$

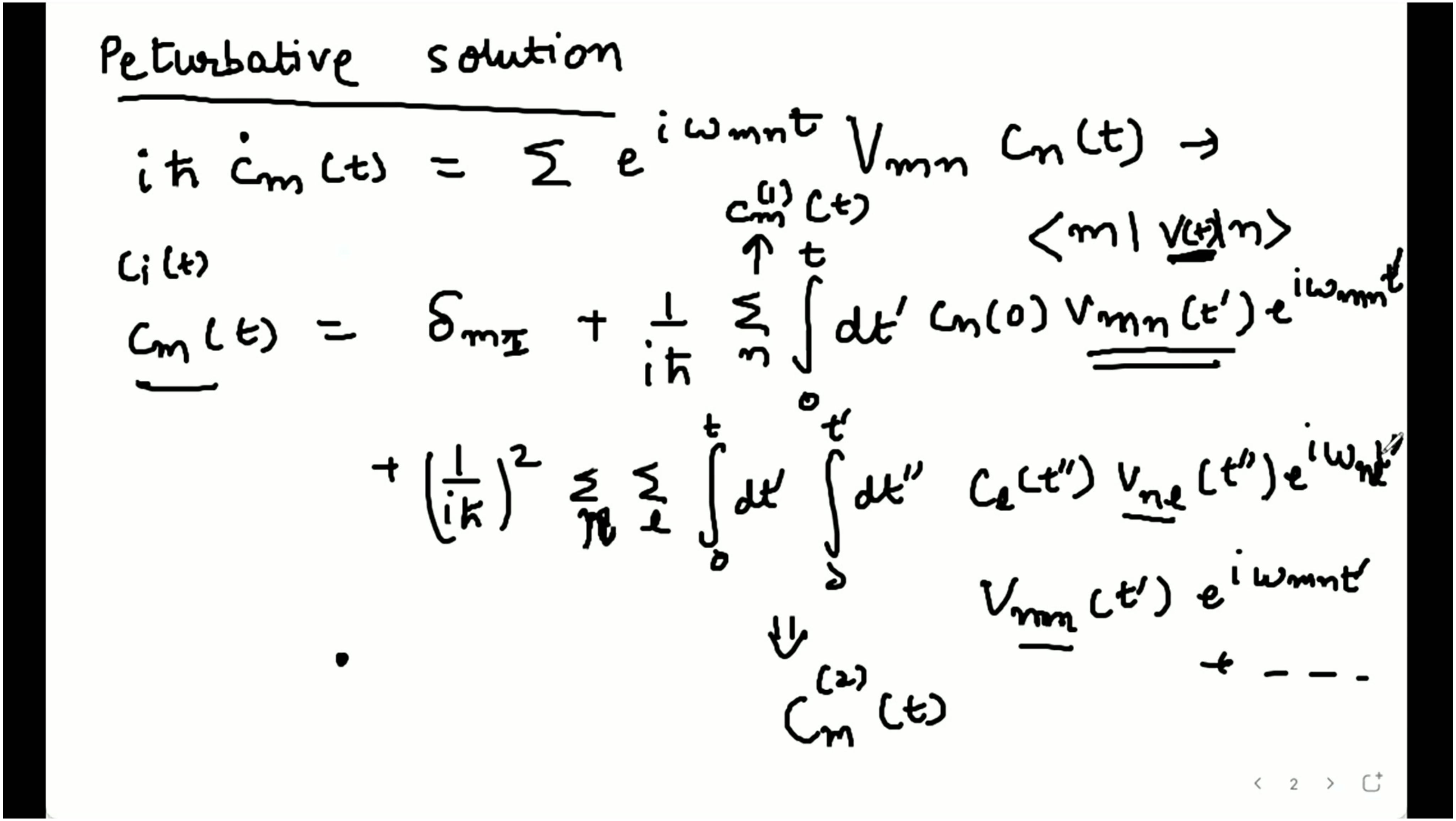
$c_i(t)$

$$\underline{c_m}(t) = \delta_{mI} + \frac{1}{i\hbar}\sum_n \int_0^t dt'\, c_n(0)\,\underline{\underline{V_{mn}(t')}}\,e^{i\omega_{mn}t'}$$

$$+ \left(\frac{1}{i\hbar}\right)^2 \sum_n \sum_l \int_0^t dt' \int_0^{t'} dt''\; c_l(t'')\,\underline{V_{nl}}(t'')\,e^{i\omega_{mn}t''}\;\underline{V_{mn}}(t')\,e^{i\omega_{mn}t'} + \cdots$$

$\Downarrow$

$c_m^2(t)$



Peturbative solution

$$i\hbar\,\dot{c}_m(t) = \sum e^{i\omega_{mn}t}\, V_{mn}\, c_n(t) \rightarrow$$

$$\langle m|\,\underline{V(t)}\,|n\rangle$$

$c_i(t)$

$$c_m^{(1)}(t)$$

$$\uparrow$$

$$\underline{c_m}(t) = \delta_{mI} + \frac{1}{i\hbar}\sum_n \int_0^t dt'\, c_n(0)\, \underline{\underline{V_{mn}(t')}}\, e^{i\omega_{mn}t'}$$

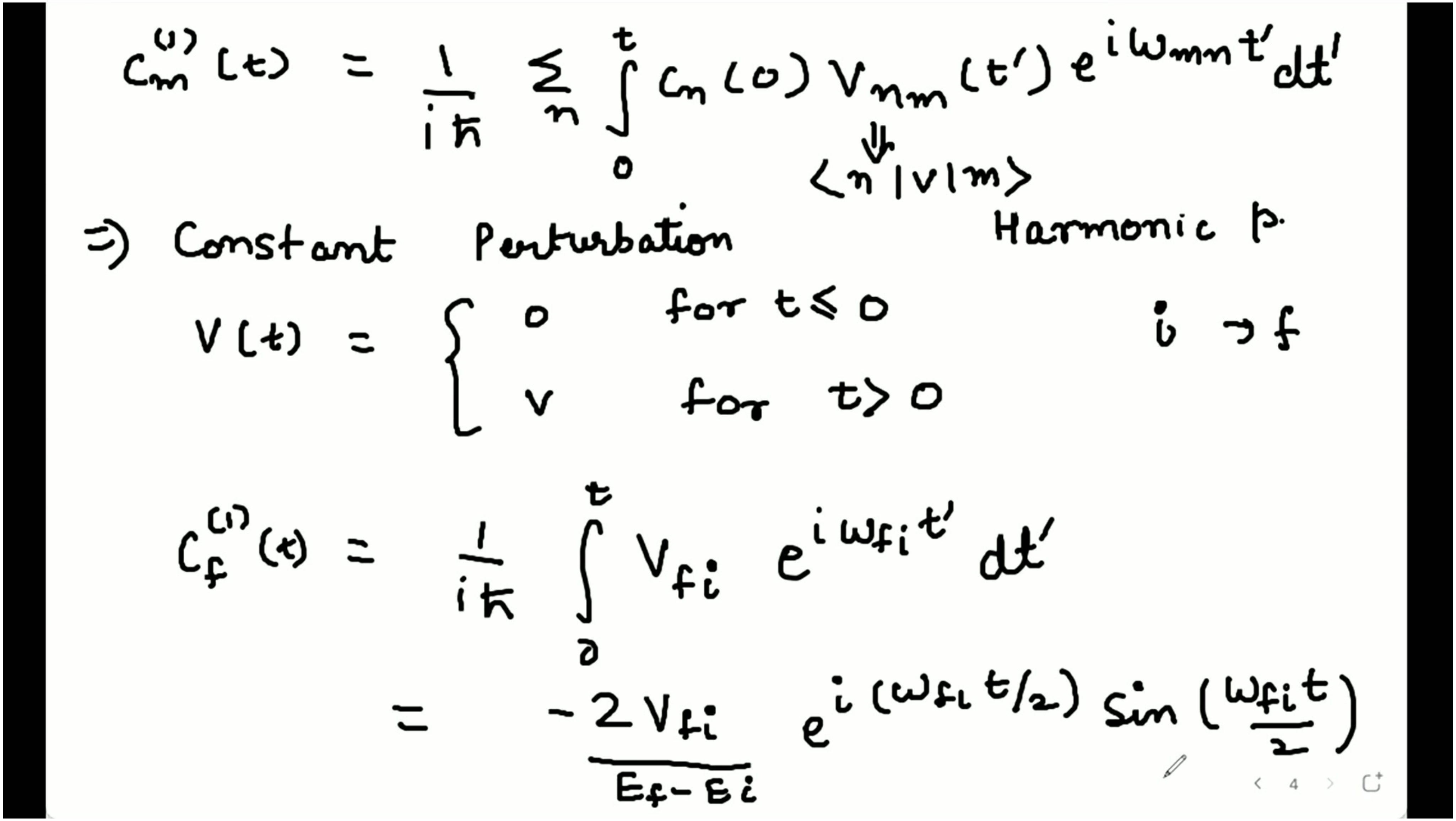
$$+\left(\frac{1}{i\hbar}\right)^2 \sum_n \sum_l \int_0^t dt' \int_0^{t'} dt''\; c_l(t'')\, \underline{V_{nl}}(t'')\, e^{i\omega_{nl}t''}$$

$$\underline{V_{mn}}(t')\, e^{i\omega_{mn}t'}$$

$$+ - - -$$

$$\Downarrow$$

$$c_m^{(2)}(t)$$



$$C_m^{(1)}(t) = \frac{1}{i\hbar}\sum_n \int_0^t C_n(0)\, \underset{\underset{\langle n|V|m\rangle}{\Downarrow}}{V_{nm}}(t')\, e^{i\omega_{mn}t'}\, dt'$$

$\Rightarrow$ Constant Perturbation Harmonic p.

$$V(t) = \begin{cases} 0 & \text{for } t \leq 0 \\ V & \text{for } t > 0 \end{cases} \qquad i \to f$$

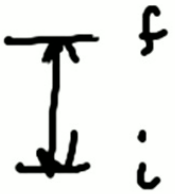
$$C_f^{(1)}(t) = \frac{1}{i\hbar}\int_0^t V_{fi}\, e^{i\omega_{fi}t'}\, dt'$$

$$= -\frac{2V_{fi}}{E_f - E_i}\, e^{i(\omega_{fi}t/2)} \sin\left(\frac{\omega_{fi}t}{2}\right)$$

Transition prob. $i \to f$

$$|c_f^{(1)}(t)|^2 = P_{i\to f} \doteq \frac{|V_{fi}|^2}{(E_f - E_i)^2} \sin^2\left(\frac{\omega_{fi} t}{2}\right)$$

1) $V_{fi} = \langle f | V | i \rangle$

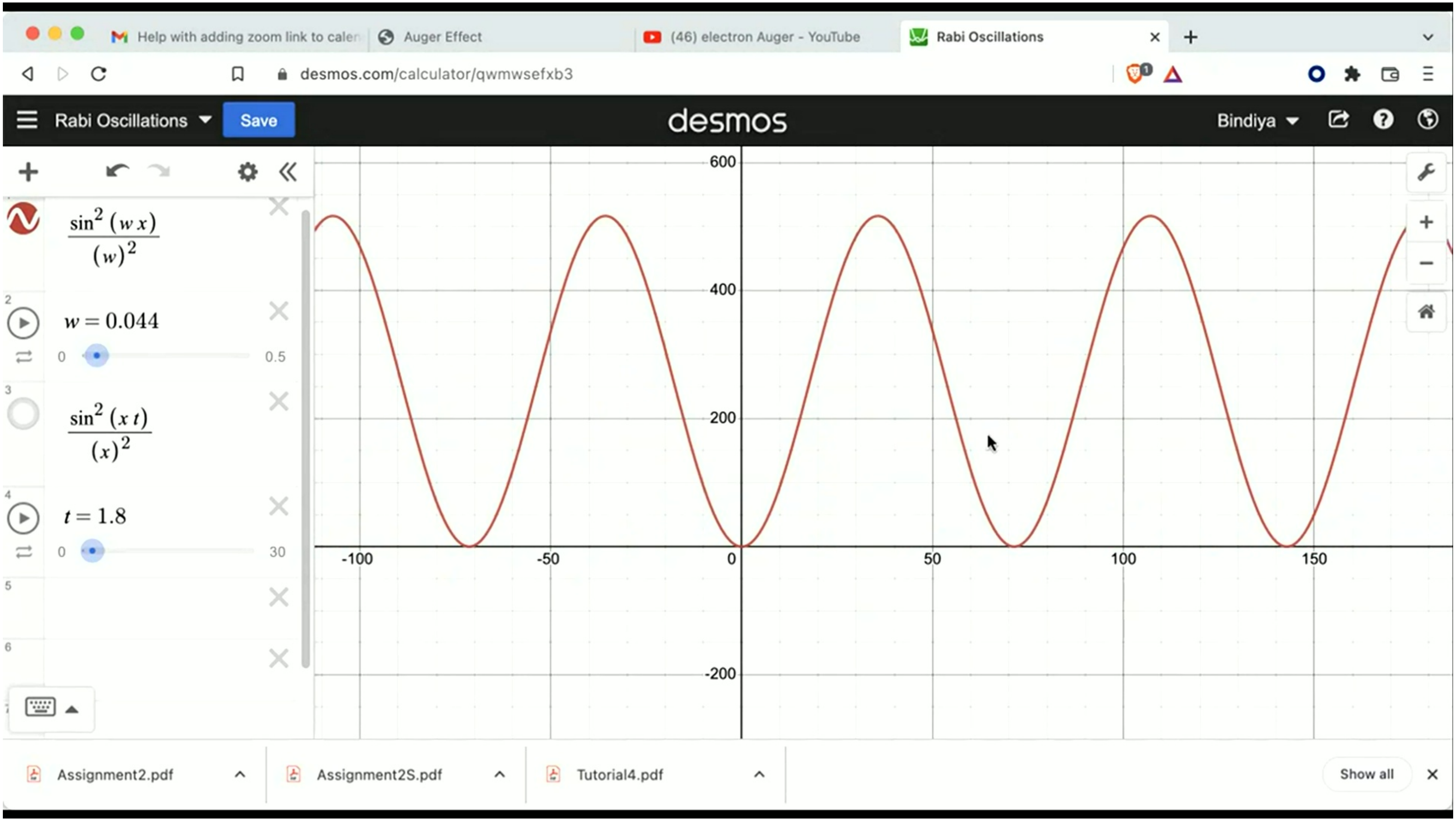


2) $\underline{\underline{(E_f - E_i)}}$

$f = i$

a) $E_f \neq E_i$ {energy non-conserving}

b) $E_f = E_i$ {energy conserving}



1 $\dfrac{\sin^2(w\,x)}{(w)^2}$

2 $w = 0.044$

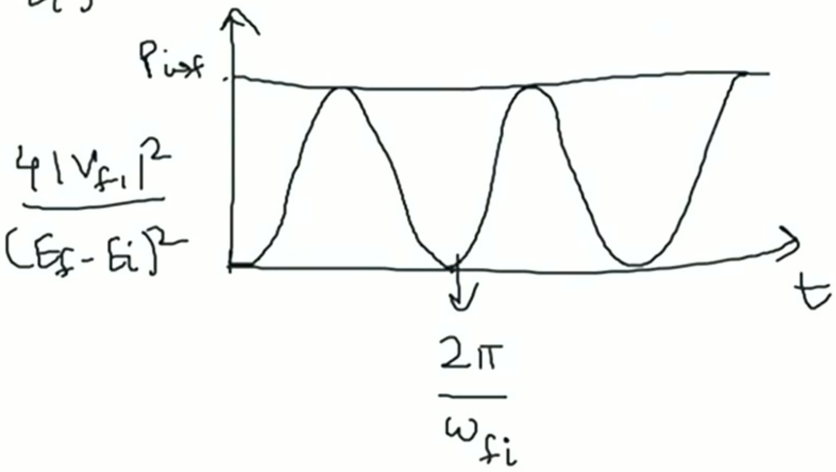
3 $\dfrac{\sin^2(x\,t)}{(x)^2}$

4 $t = 1.8$

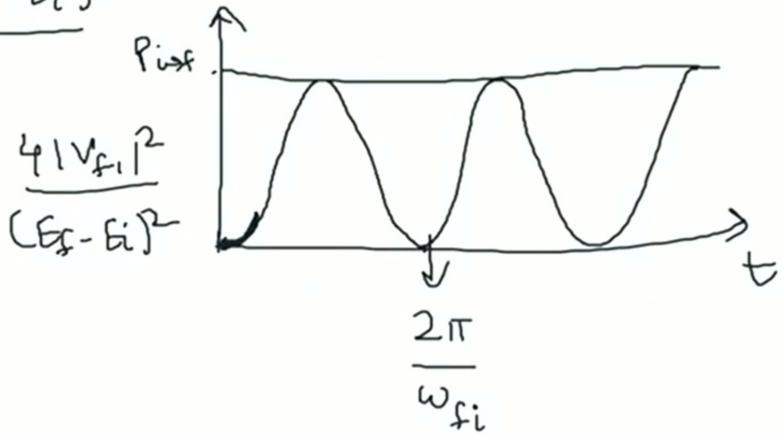
5

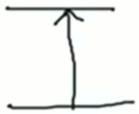
6

$$\left|C_f^{(1)}(t)\right|^2 = \frac{4\left|V_{fi}\right|^2}{(E_f-E_i)^2} \sin^2\left(\frac{\omega_{fi} t}{2}\right) \qquad t = \frac{2\pi}{\omega_{fi}}$$



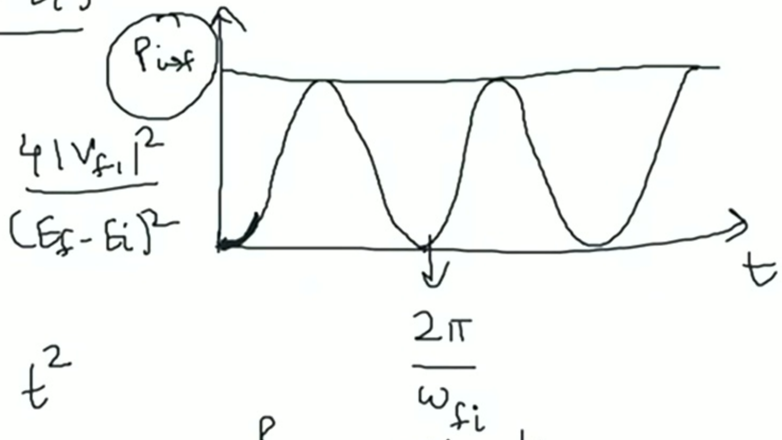
$$|C_f^{(1)}(t)|^2 = \frac{4|V_{fi}|^2}{(E_f-E_i)^2}\underbrace{\sin^2\left(\frac{\omega_{fi}t}{2}\right)}_{} \propto t^2 \qquad t = \frac{2\pi}{\omega_{fi}}$$

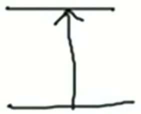




P_f

$$|C_f^{(1)}(t)|^2 = 4\frac{|V_{fi}|^2}{(E_f-E_i)^2}\underbrace{\sin^2\left(\frac{\omega_{fi}t}{2}\right)} \propto t^2 \qquad t = \frac{2\pi}{\omega_{fi}}$$





$E_f \neq E_i$

$P_{f\to i} \propto t^2$

$W = \frac{P}{t} \propto t$

$$\frac{P_{f\to i} \propto t}{}$$

$\boxed{W} \Rightarrow \frac{P}{t} \Rightarrow$ constant.

$\Downarrow$

transition

$P_{f\to i} \propto t^2$

$\overline{\omega_{fi}}$

$P_{f\to i} \propto t$

$w = \frac{P}{t} \propto t$

$\underset{\substack{\Downarrow \\ \text{transition}}}{\textcircled{W}} \Rightarrow \frac{P}{t} \Rightarrow$ constant.

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b) $E_f = E_i$ $\qquad E_f \to E_i$

Lim
E

$$\omega_{fi}$$

$$P_{f\to i} \propto t$$

$$w = \frac{P}{t} \propto t$$

$$\boxed{W} \Rightarrow \frac{P}{t} \Rightarrow \text{constant.}$$

$\Downarrow$
transition

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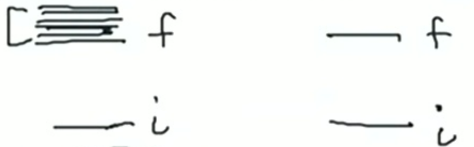
b) $E_f = E_i$ $\quad \boxed{E_f} \to \boxed{E_i}$

$$\lim_{E_f \to E_i} P_{f\to i}(t) = \frac{|V_{fi}|^2\, t^2}{\hbar^2}$$



$$\boxed{\begin{matrix} E_i = E_f \\ i \neq f. \end{matrix}}$$

$E_i = E_f$
$i = f$

$_{f\to i}$ $_{fi}$

$$P_{f\to i} \cancel{\propto} t$$

$$w = \frac{P}{t} \propto t$$

$$\boxed{W} \Rightarrow \frac{P}{t} \Rightarrow \text{constant.}$$

$\Downarrow$
transition

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b) $E_f = E_i$

$$\boxed{E_f} \rightarrow \boxed{E_i}$$

$\rho(E_f) \leftarrow [\equiv f\,] \rightarrow$ — f

density of state

— i — i $E_i = E_f$

$i = f$

$$\boxed{\begin{array}{c} E_i = E_f \\ i \neq f. \end{array}}$$

$$\lim_{E_f \to E_i} P_{f\to i}(t) = \frac{|V_{fi}|^2 t^2}{\hbar^2}$$

$\rho(E_f) \rightarrow$ no. of states per unit Energy around

$E_f \to E_i$ $\hbar$

$\rho(E_f) \to$ no. of states per unit Energy around E

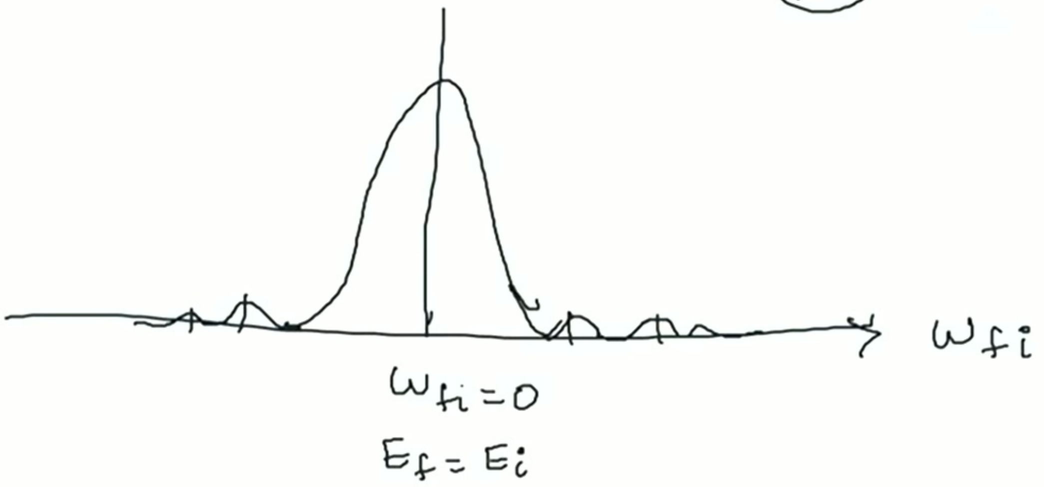
$$\sum P_{i\to f}(t) = \int \overset{|V_{fi}|^2}{\underline{P_{i\to f}(t)}}\; \underbrace{\rho\,(E_f)}\, d E_f$$

$$= \underline{\frac{4\,|V_{fi}|^2 \rho\,(E_f)}{\hbar^2}} \int \frac{\sin^2(\omega_{fi}\,t/2)}{\omega_{fi}^2}$$

$E_f - E_i < 0$

$E_f - E_i < 0$

$$= \frac{4|V_{fi}|^2 \rho(E_f)}{\hbar^2} \int \frac{\sin^2(\omega_{fi} t/2)}{\omega_{fi}^2} d\omega_{fi}$$



$\omega_{fi} = 0$

$E_f = E_i$

$$\sum_f P_{i \to f}(t) = \frac{2\pi |V_{fi}|^2}{\hbar} \rho(E_f)\, t$$

$E_f = E_i$

$$\sum_f P_{i \to f}(t) = \frac{2\pi |V_{fi}|^2}{\hbar} \rho(E_f)\, t$$

$$\boxed{W = \frac{P}{t}} = \text{const wrt } t$$

$E_i = E_f$

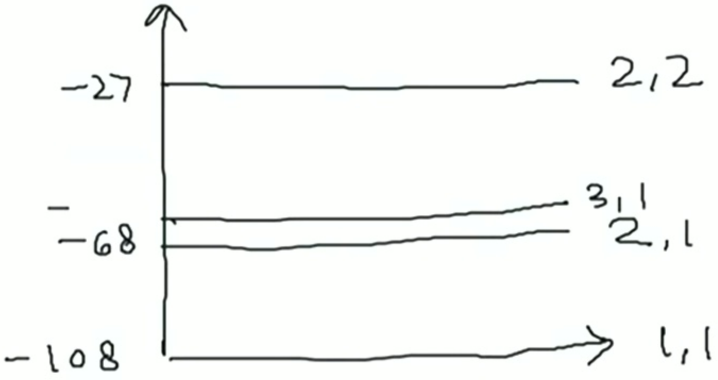
$i \neq f$

self ioni

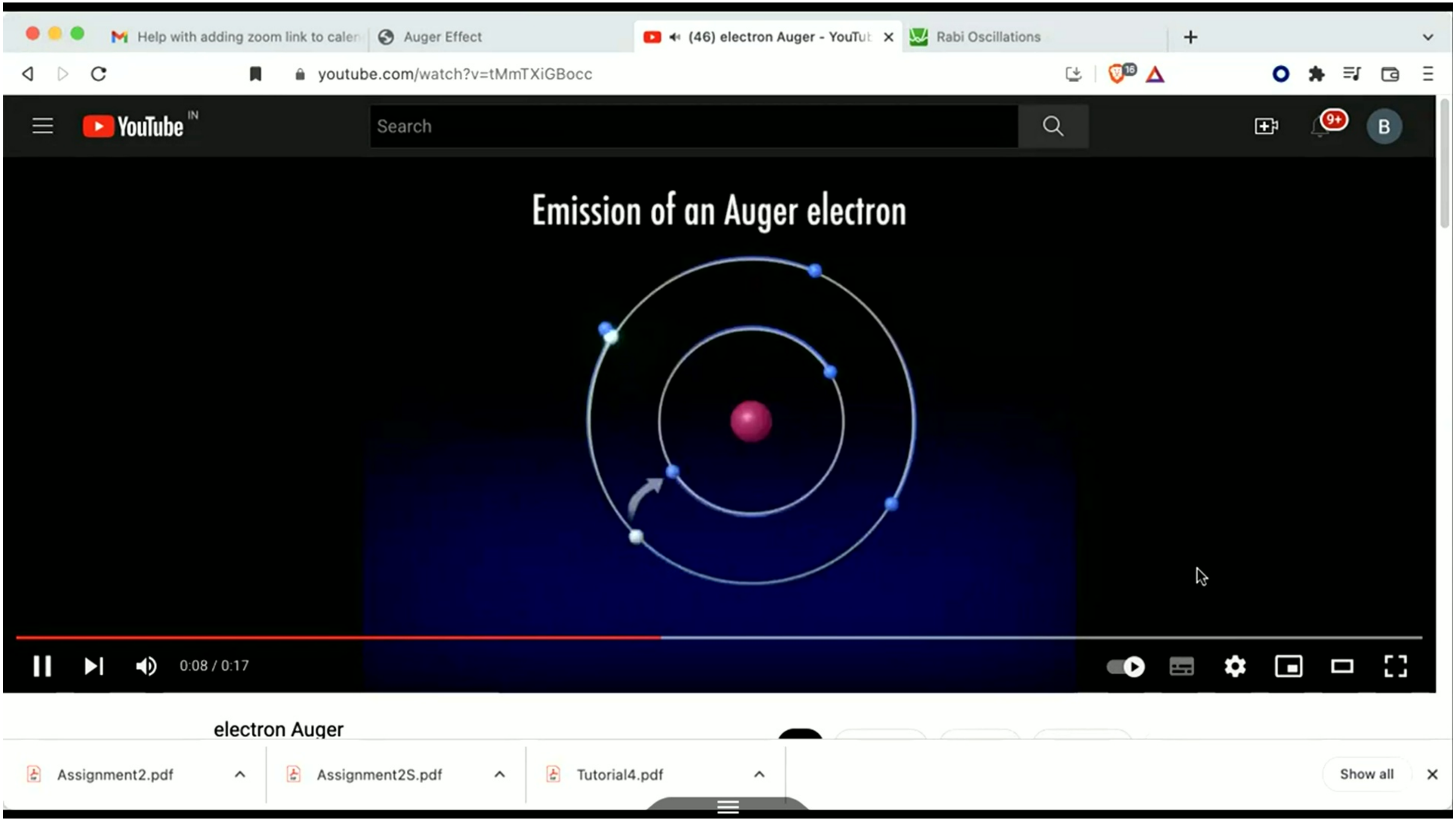
Self ionization   Auger   Autoionization

He   2

$$E_{n_1,n_2} = -54.4\left[\frac{1}{n_1^2} + \frac{1}{n_2^2}\right]$$



$1s^2$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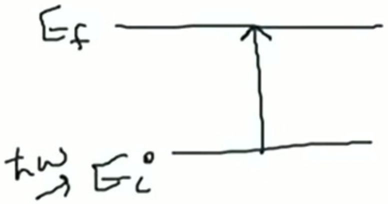
Harmonic perturbation

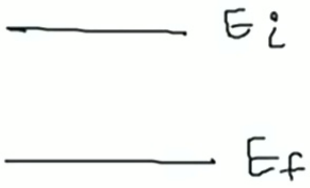
$$V(t) = \begin{cases} 0 & t \leq 0 \\ V_0 e^{i\omega t} + V_0^{\dagger} e^{-i\omega t} & t > 0 \end{cases}$$

$$\left(C_f^{(1)}(t)\right) = \frac{-V_{fi}}{\hbar}\left[\frac{e^{i(\omega_{fi}+\omega)t}-1}{\omega_{fi}+\omega} + \frac{e^{i(\omega_{fi}-\omega)t}-1}{\omega_{fi}-\omega}\right]$$

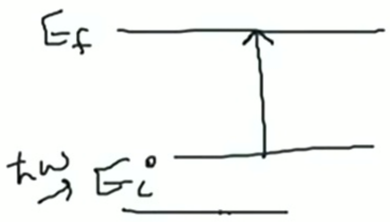
2) → $\omega_{fi} - \omega \simeq 0 \Rightarrow E_f = E_i + \underline{\underline{\hbar\omega}}$



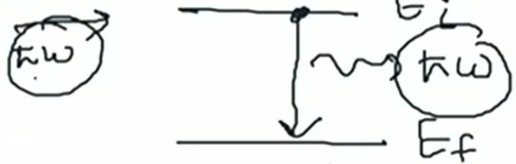
1) → $\omega_{fi} + \omega \simeq 0$ $E_f = E_i - \hbar\omega$



2) → $\omega_{fi} - \omega \simeq 0 \Rightarrow E_f = E_i + \underline{\underline{\hbar\omega}}$



1) → $\omega_{fi} + \omega \simeq 0$ $E_f = E_i - \hbar\omega$



Stimulated emission