Hydrogen transition 1

Start with the perturbing Hamiltonian (E_0 is peak electric field in newtons per coulomb).

$$H_1(\mathbf{r},t) = -\frac{eE_0\boldsymbol{\epsilon}\cdot\mathbf{p}}{m\omega}\cos(\mathbf{k}\cdot\mathbf{r}-\omega t)$$

In exponential form

$$H_1(\mathbf{r},t) = -\frac{eE_0\boldsymbol{\epsilon}\cdot\mathbf{p}}{m\omega}\left(\tfrac{1}{2}\exp(i\mathbf{k}\cdot\mathbf{r}-i\omega t)+\tfrac{1}{2}\exp(-i\mathbf{k}\cdot\mathbf{r}+i\omega t)\right)$$

Given the initial condition $c_b(0)=0$ the first-order approximation for $c_b(t)$ is

$$c_b(t) = -\frac{i}{\hbar}\int_0^t \langle\psi_b|H_1(\mathbf{r},t')|\psi_a\rangle\exp(i\omega_0 t')\,dt',\quad \omega_0=\frac{E_b-E_a}{\hbar}$$

Factor the integrand.

$$\begin{aligned}c_b(t) = \frac{ieE_0}{2\hbar m\omega}\langle\psi_b|\boldsymbol{\epsilon}\cdot\mathbf{p}\exp(i\mathbf{k}\cdot\mathbf{r})|\psi_a\rangle\int_0^t\exp(-i\omega t')\exp(i\omega_0 t')\,dt'\\ +\frac{ieE_0}{2\hbar m\omega}\langle\psi_b|\boldsymbol{\epsilon}\cdot\mathbf{p}\exp(-i\mathbf{k}\cdot\mathbf{r})|\psi_a\rangle\int_0^t\exp(i\omega t')\exp(i\omega_0 t')\,dt'\end{aligned}$$

Solve the integrals to obtain

$$\begin{aligned}c_b(t) = \frac{eE_0}{2\hbar m\omega}\langle\psi_b|\boldsymbol{\epsilon}\cdot\mathbf{p}\exp(i\mathbf{k}\cdot\mathbf{r})|\psi_a\rangle\frac{\exp\big(i(\omega_0-\omega)t\big)-1}{\omega_0-\omega}\\ +\frac{eE_0}{2\hbar m\omega}\langle\psi_b|\boldsymbol{\epsilon}\cdot\mathbf{p}\exp(-i\mathbf{k}\cdot\mathbf{r})|\psi_a\rangle\frac{\exp\big(i(\omega_0+\omega)t\big)-1}{\omega_0+\omega}\end{aligned}\tag{1}$$

As an approximation, discard the second term since the first term dominates for $\omega\approx\omega_0$.

$$c_b(t) = \frac{eE_0}{2\hbar m\omega}\langle\psi_b|\boldsymbol{\epsilon}\cdot\mathbf{p}\exp(i\mathbf{k}\cdot\mathbf{r})|\psi_a\rangle\frac{\exp\big(i(\omega_0-\omega)t\big)-1}{\omega_0-\omega}$$

Rewrite $c_b(t)$ in the form of a sine function.

$$c_b(t) = \frac{ieE_0}{\hbar m\omega}\langle\psi_b|\boldsymbol{\epsilon}\cdot\mathbf{p}\exp(i\mathbf{k}\cdot\mathbf{r})|\psi_a\rangle\frac{\sin\big(\frac{1}{2}(\omega_0-\omega)t\big)}{\omega_0-\omega}\exp\big(\tfrac{i}{2}(\omega_0-\omega)t\big)\tag{2}$$

Verify dimensions.

$$\frac{eE_0\boldsymbol{\epsilon}\cdot\mathbf{p}}{m\omega} = \frac{\overset{\displaystyle e}{\text{coulomb}}\quad\overset{\displaystyle E_0}{\text{newton}\,\text{coulomb}^{-1}}\quad\overset{\displaystyle \boldsymbol{\epsilon}\cdot\mathbf{p}}{\text{momentum}}}{\underset{\text{kilogram}}{m}\quad\underset{\text{second}^{-1}}{\omega}} = \text{joule}$$

$$c_b(t) = \frac{\overset{\displaystyle e}{\text{coulomb}}\quad\overset{\displaystyle E_0}{\text{newton}\,\text{coulomb}^{-1}}}{\underset{\text{joule}\,\text{second}}{\hbar}\quad\underset{\text{kilogram}}{m}\quad\underset{\text{second}^{-1}}{\omega}}\;\frac{\overset{\displaystyle \langle\psi_b|\boldsymbol{\epsilon}\cdot\mathbf{p}\exp(i\mathbf{k}\cdot\mathbf{r})|\psi_a\rangle}{\text{momentum}}}{\underset{\text{second}^{-1}}{\omega_0-\omega}} = 1$$

Wave functions ψ_a and ψ_b have dimension meter$^{-1/2}$ which cancel with $dx=$ meter when integrated.