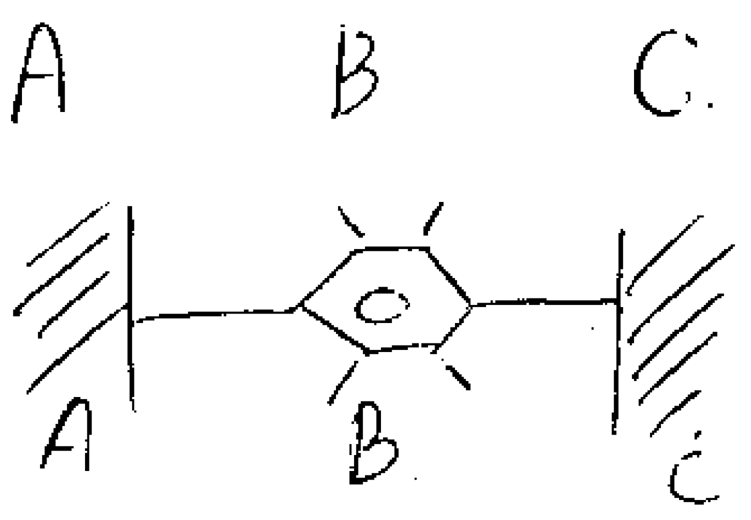
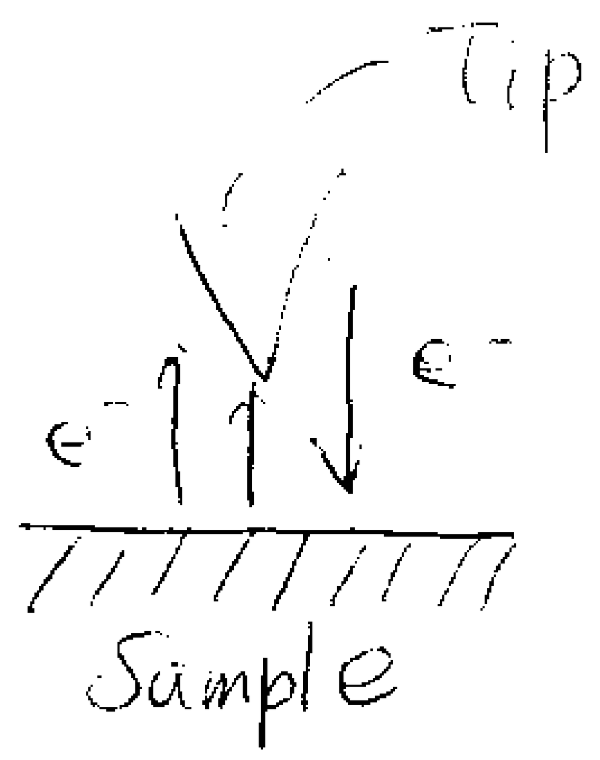
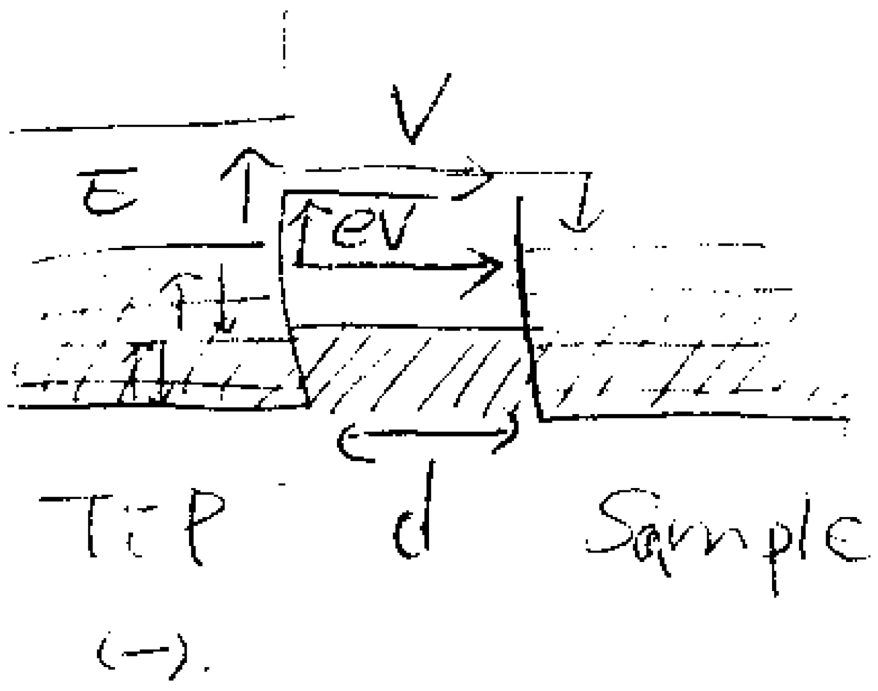
Sheet ________ Date 11.17







E< V

d↓, 전류 흐름

터널링

$$i\hbar\frac{\partial\psi(t_b\, t_c)}{\partial t_b} = E\psi(t_b t_a)$$

$$\psi(t_b t_a) = U(t_b t_a)\psi(t_a)$$

$$U^0(t\, t_a) = \exp\frac{E}{i\hbar}(t-t_a)$$

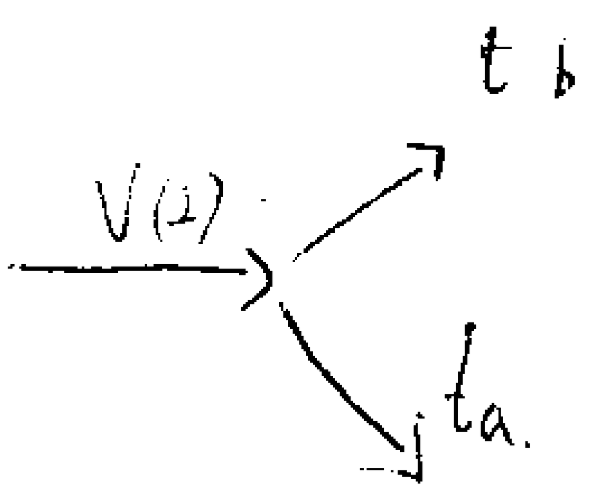
↑

$$\boxed{H = H^0 + V}$$

$$U(t\, t_a) = U^0(t\, t_a) + U^1(t, t_a) + U^{(2)}(t, t_a) + \cdots + U^{(k)}(t, t_a) +$$

↓

$$\left(\frac{1}{i\hbar}\right)^k \iiint U^0 V U^0$$



$$\int_{t_a}^{t} dz\, U^0(t z)\, V(z)\, U^0(\tau\, t_a)$$

$$\psi^{(1)}(t\, t_a)\left(\frac{1}{i\hbar}\right)\int dz\, U^0(t, z)\underbrace{|b\rangle\langle b|}_{1} V(z)\, U^0(\tau\, t_a)\overset{|a\rangle}{\psi(t_a)}$$

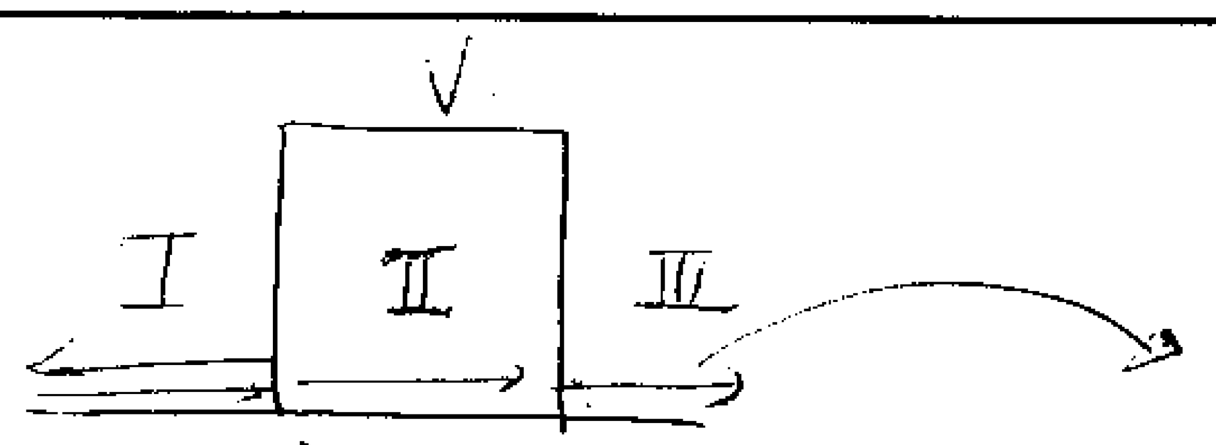
$$f = \Sigma|k\rangle\langle k|f\rangle$$

$$1 = \Sigma|k\rangle\langle k|$$

$$\psi^{(t\, t_a)}_{a\to b} = \left(\frac{1}{i\hbar}\right)\int_{t_a}^{t} \exp^{\frac{\overset{\hbar\omega_b}{E_b}}{i\hbar}(t-z)} \langle b|V \exp^{\frac{\overset{\hbar\omega_a}{E_a}}{i\hbar}(\tau-t_a)} |a\rangle$$

$$U^0(\tau\, t_a) = \exp^{\frac{H}{i\hbar}(\tau-t_a)}|a\rangle, \quad \left[1+\frac{H}{i\hbar}(\tau-t_a)\right]|a\rangle$$

=



$$i\hbar \frac{\partial \phi(r,t)}{\partial t} = E\phi(r,t) \quad // \ \phi(r)g(t)$$

$$i\hbar \frac{\partial g(t)}{\partial t} = E g(t), \quad g(t) = g \exp^{-\frac{E}{\hbar}t}$$

E. A. E

I

$$-\frac{\hbar^2}{2m}\nabla_x^2 \psi_I = E\psi_I$$

$$\downarrow \ \frac{2mE}{\hbar^2} = p^2$$

$$\frac{\partial^2 \phi_I}{\partial x^2} + p^2 \phi_I = 0.$$

$$\phi_I = A e^{ipx} + B e^{-ipx}$$

$A = 1$, $B = R$

$$\phi_I(r,t) = Ae^{i(px-\omega t)} \rightarrow + Be^{i(px+\omega t)}$$

$\leftarrow$ 반사

II

$$\left[-\frac{\hbar^2}{2m}\nabla_x^2 + V\right]\phi_{II} = E\phi_{II}$$

$$\frac{\partial^2 \phi_{II}}{\partial x^2} - k^2 \phi_{II} = 0 \qquad \sqrt{\frac{2m(V-E)}{\hbar}}$$

$$\phi_{II} = Ce^{-kx} + De^{kx}$$

$$Ce^{i(kx-\omega t)}$$

III

$$\left[-\frac{\hbar^2}{2m}\nabla_x^2 + 0\right]\phi_{III} = E\phi_{III}$$

$$\frac{2mE}{\hbar^2} = p^2$$

$$\frac{\partial^2 \phi_{III}}{\partial x^2} + p^2 \phi_{III} = 0$$

$$\phi_{III} = f e^{ipx} \qquad \sqrt{2mE}$$

$f = T$. 투과

$$\psi_I = e^{i\frac{p}{\hbar}x} + Re^{-i\frac{p}{\hbar}x}$$

$$p = \sqrt{2mE}$$

* Boundary Condition

① $\phi_I(0) = \phi_{II}(0)$

② $\left.\frac{\partial \phi_I}{\partial x}\right|_{x=0} = \left.\frac{\partial \phi_{II}}{\partial x}\right|_{x=0}$

③ $\phi_{II}(d) = \phi_{III}(d)$

④ $\left.\frac{\partial \phi_{II}}{\partial x}\right|_{x=L} = \left.\frac{\partial \phi_{II}}{\partial x}\right|_{x=0}$

* T 구하기 (T^2)

① $1 + R = C + D$

② $\frac{ip}{\hbar}[1-R] = k[C-D]$

③ $ke^{kd}[C - De^{-2kd}] = i\frac{p}{\hbar}T$

④ $ke^{kd}[C - De^{-2kd}] = i\frac{p}{\hbar}T$

$$\begin{bmatrix} R \\ C \\ D \\ T \end{bmatrix} = \begin{bmatrix} -1 & 1 & 1 & 0 \\ \triangle p & \hbar k & \hbar k & 0 \\ 0 & e^{kd} & -e^{kd} & 1 \\ 0 & & & pi \end{bmatrix}^{-1} \begin{bmatrix} 1 \\ ip \\ 0 \\ 0 \end{bmatrix}$$

$-\hbar k e^{kd}$ $\quad$ $\hbar k e^{-kd}$

$$= \frac{1}{i\hbar}\int_{t_a}^{t} \exp^{i(\omega_b-\omega_a)\tau} \exp^{\frac{i}{\hbar}(t_a-t)} \overbrace{\langle b|V|a\rangle}^{=V_{ba}} |a\rangle$$

$$= \frac{1}{i\hbar} \exp\frac{i}{\hbar}[t_a-t]\, V_{ba}|a\rangle \int_0^t d\tau \exp^{i\overbrace{(\omega_b-\omega_a)}^{=\omega_{ba}}\tau} \qquad \frac{\exp^{i\omega_{ba}}}{i\omega_{ba}}\Big|_0^t$$

$$|\psi(t, t_a)_{a\to b}|^2 = \frac{1}{\hbar^2}|V_{ba}|^2 \left[\frac{\exp^{i\omega t}}{i\omega_{ab}}\Big|_0^t\right]^2$$

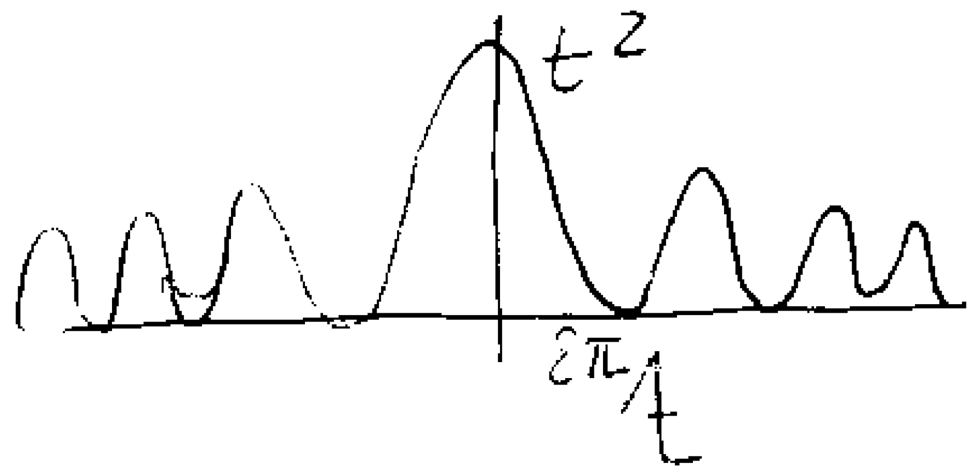
$$= \frac{1}{\hbar^2}|V_{ba}|^2 \frac{2(1-\cos\omega_{ab}t)}{\omega_{ab}^2}, \qquad \underbrace{1+1-(e^{i\omega t}+e^{-i\omega t})}_{2\cos\omega_{ab}t}$$

$$\delta(\omega_{ab})t$$

Delta function.

$$\delta(\omega) = \frac{1}{\pi}\lim_{t\to\infty}\frac{1-\cos\omega t}{t\omega^2}$$

$$\Rightarrow \pi\delta(\omega_{ab})t$$



$$\delta(ax) = \frac{1}{|a|}\delta(x).$$

$$|\psi(t,0)_{a\to b}|^2 = \frac{1}{\hbar^2}|V_{ab}|^2\, 2\pi\delta(\overbrace{\omega_{ab}}^{\frac{E_b - E_a}{i\hbar}})t$$

$$= \frac{1}{\hbar^2}|V_{ab}|^2\, 2\pi\delta(E_b-E_a)t\hbar$$

$$\boxed{\frac{\partial|\psi(t,0)_{a\to b}|^2}{\partial t} = \frac{2\pi}{\hbar}|V_{ab}|^2\,\delta(E_b-E_a)}$$

golden's rule

$E_a + \hbar\omega$

E conservation 유지될때.
tunneling 일어남.