

## WKB method part 2

Let  $V(x)$  be the following barrier potential.

$$V(x) = \begin{cases} 0 & x < 0 \\ V_0 & 0 \leq x \leq L \\ 0 & x > L \end{cases}$$

Find tunneling probability  $T$  for a particle with mass  $m$  and energy  $E < V_0$ .

We have the following Schrodinger equations, one for each region of  $V(x)$ .

$$\begin{aligned} -\frac{\hbar^2}{2m} \frac{d^2}{dx^2} \psi_1 &= E\psi_1 & x < 0 \\ -\frac{\hbar^2}{2m} \frac{d^2}{dx^2} \psi_2 + V_0\psi_2 &= E\psi_2 & 0 \leq x \leq L \\ -\frac{\hbar^2}{2m} \frac{d^2}{dx^2} \psi_3 &= E\psi_3 & x > L \end{aligned}$$

Let  $\psi_1$  and  $\psi_3$  have the most general free-particle solutions.

$$\begin{aligned} \psi_1(x) &= A \exp\left(i\sqrt{\frac{2mE}{\hbar^2}}x\right) + B \exp\left(-i\sqrt{\frac{2mE}{\hbar^2}}x\right) \\ \psi_3(x) &= F \exp\left(i\sqrt{\frac{2mE}{\hbar^2}}x\right) + G \exp\left(-i\sqrt{\frac{2mE}{\hbar^2}}x\right) \end{aligned}$$

Use the WKB method to solve for  $\psi_2$ .

$$\psi_2(x) = C \exp\left(i \int \sqrt{\frac{2m(E - V_0)}{\hbar^2}} dx\right) + D \exp\left(-i \int \sqrt{\frac{2m(E - V_0)}{\hbar^2}} dx\right)$$

Cancel  $i$  by swapping  $E$  and  $V_0$ .

$$\psi_2(x) = C \exp\left(\int \sqrt{\frac{2m(V_0 - E)}{\hbar^2}} dx\right) + D \exp\left(-\int \sqrt{\frac{2m(V_0 - E)}{\hbar^2}} dx\right)$$

Noting that

$$\int \sqrt{\frac{2m(V_0 - E)}{\hbar^2}} dx = \sqrt{\frac{2m(V_0 - E)}{\hbar^2}} x$$

we have

$$\psi_2(x) = C \exp\left(\sqrt{\frac{2m(V_0 - E)}{\hbar^2}} x\right) + D \exp\left(-\sqrt{\frac{2m(V_0 - E)}{\hbar^2}} x\right)$$

To simplify the formulas let

$$k = \sqrt{\frac{2mE}{\hbar^2}} \quad \beta = \sqrt{\frac{2m(V_0 - E)}{\hbar^2}}$$

and write

$$\begin{aligned}\psi_1(x) &= A \exp(ikx) + B \exp(-ikx) \\ \psi_2(x) &= C \exp(\beta x) + D \exp(-\beta x) \\ \psi_3(x) &= F \exp(ikx) + G \exp(-ikx)\end{aligned}$$

Exponentials of  $-i$  represent particles moving from right to left. The  $B$  exponential represents a particle reflected from the boundary at  $x = 0$ . There is no particle moving right to left at  $x > L$  hence  $G = 0$ .

Let us now solve for the coefficients using boundary conditions. Four boundary conditions are needed to ensure continuity at  $x = 0$  and  $x = L$ .

Boundary conditions at  $x = 0$ .

$$\begin{aligned}\psi_1(0) &= \psi_2(0) \\ \psi_1'(0) &= \psi_2'(0)\end{aligned}$$

Boundary conditions at  $x = L$ .

$$\begin{aligned}\psi_2(L) &= \psi_3(L) \\ \psi_2'(L) &= \psi_3'(L)\end{aligned}$$

From the boundary condition  $\psi_2(L) = \psi_3(L)$  we have

$$C \exp(\beta L) + D \exp(-\beta L) = F \exp(ikL) \quad (1)$$

From the boundary condition  $\psi_2'(L) = \psi_3'(L)$  we have

$$\beta C \exp(\beta L) - \beta D \exp(-\beta L) = ikF \exp(ikL) \quad (2)$$

Add  $\beta$  times (1) to (2) to obtain

$$2\beta C \exp(\beta L) = (\beta + ik)F \exp(ikL)$$

Hence

$$C = \frac{(\beta + ik)F \exp(ikL - \beta L)}{2\beta} \quad (3)$$

Add minus  $\beta$  times (1) to (2) to obtain

$$-2\beta D \exp(-\beta L) = (-\beta + ik)F \exp(ikL)$$

Hence

$$D = \frac{(\beta - ik)F \exp(ikL + \beta L)}{2\beta} \quad (4)$$

From the boundary condition  $\psi_1(0) = \psi_2(0)$  we have

$$A + B = C + D \quad (5)$$

From the boundary condition  $\psi'_1(0) = \psi'_2(0)$  we have

$$ik(A - B) = \beta(C - D) \quad (6)$$

Add  $ik$  times (5) to (6) to obtain

$$2ikA = \beta(C - D) + ik(C + D)$$

Hence

$$A = \frac{\beta(C - D)}{2ik} + \frac{C + D}{2}$$

Substitute (3) and (4) for  $C$  and  $D$  to obtain

$$A = F \exp(ikL) (\cosh(\beta L) + i\gamma \sinh(\beta L)) \quad (7)$$

where

$$\gamma = \frac{1}{2} \left( \frac{\beta}{k} - \frac{k}{\beta} \right)$$

Tunneling probability  $T$  is

$$T = \left| \frac{F}{A} \right|^2 = \left| \frac{1}{\exp(ikL) (\cosh(\beta L) + i\gamma \sinh(\beta L))} \right|^2$$

Hence

$$T = \frac{1}{\cosh^2(\beta L) + \gamma^2 \sinh^2(\beta L)} \quad (8)$$

Equivalently

$$T = \left[ 1 + \frac{V_0^2}{4E(V_0 - E)} \sinh^2(\beta L) \right]^{-1} \quad (9)$$

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