# Is the speed of light in tunneling faster than the speed of light in a vacuum???

(In these cases, physicists still don't understand the nature of time tunneling in a potential well.)

In classical physics, if we want to know how long it takes a particle to travel, we need to know the start and end times. But in quantum models, such as the "quantum clock" model, all we can observe and measure is the time difference (or travel time), not the absolute start time.

(There is no universal reference point for determining when the tunneling started.)

When the clock shows that the particle has only been inside the barrier for "say, 1 femtosecond," but because we don't know when that 1 femtosecond started, we can't tell the information from one point to another.

This is one of the main reasons why quantum tunneling remains consistent with special relativity, even though the "effective passage speed" apparently exceeds the speed of light.

In quantum mechanics, we can never say with certainty "when" a particle entered a particular region (e.g., a potential well). Not yesterday, not today, not in the future.

(I can only enter the well, see it, and calculate the time difference.)

The papers have explained the matter very vaguely. In short, the phase velocity can exceed the speed of light, but that does not mean that information can also travel at the speed of light. Of course, today's experiments say so. I believe that information will travel faster than the speed of light in the future. Of course, we know that the phase velocity can travel faster than light. In quantum, if we make the well bigger or smaller, we will observe the same amount of tunneling time. That is, time is constant whether we increase or decrease the distance. This does not fit with classical theory because if the distance is bigger, the time to travel the distance should be longer. But in quantum mechanics, this is not the case and time will be the same. Of course, if we shine light on the glass and gradually increase its width, we will see that the transmission does not change to any extent and returns to its previous state (Faynman)

I believe that if we make the space smaller, the dispersion of the space will decrease by taking into account the uncertainty principle and we will witness the dispersion of momentum and as a result of this event, we will observe that the phase fluctuation will increase and as a result of the increase in the phase I will observe that the time will be less or in other words I increased the kinetic energy and the transit time has decreased and as a result we can say that the phase velocity has increased and we can say that we will have a constant time and we know that the probability current density is obtained from the Schrodinger equation and this relationship can be said that the probability current density has increased as a result of the decrease in the dispersion of the location of the probability current density and as a result this time in tunneling has decreased and my solution can be said that this can be said that I will have a constant time

Different methods There are formulas for getting the time it takes for a particle to pass through a well, but what caught my attention was the residence time formula, which doesn't give the time it takes for the particle to pass through, but rather the time it is there. I tried to come up with a new formula, but I had problems with dimensions and couldn't come up with a formula that had the time dimension and the necessary standards, but my formula was very similar to the residence time formula, or my way of thinking was similar to the residence time formula. article amsmath physics

## Derivation of the Probability Current from the Schrödinger Equation

We begin with the time-dependent Schrödinger equation in one dimension:

$$i\hbar \frac{\partial \psi}{\partial t} = -\frac{\hbar^2}{2m}\frac{\partial^2 \psi}{\partial x^2} + V(x)\psi \tag{1}$$

and its complex conjugate:

$$-i\hbar \frac{\partial \psi^*}{\partial t} = -\frac{\hbar^2}{2m}\frac{\partial^2 \psi^*}{\partial x^2} + V(x)\psi^* \tag{2}$$

The probability density is defined as:

$$\rho(x,t) = \psi^*(x,t)\psi(x,t)$$

Taking the time derivative:

$$\frac{\partial \rho}{\partial t} = \psi^* \frac{\partial \psi}{\partial t} + \psi \frac{\partial \psi^*}{\partial t} \tag{3}$$

Substitute from the Schrödinger equation and its conjugate:

$$\begin{aligned}
\frac{\partial \psi}{\partial t} &= \frac{1}{i\hbar}\left(-\frac{\hbar^2}{2m}\frac{\partial^2 \psi}{\partial x^2} + V\psi\right) \\
\frac{\partial \psi^*}{\partial t} &= -\frac{1}{i\hbar}\left(-\frac{\hbar^2}{2m}\frac{\partial^2 \psi^*}{\partial x^2} + V\psi^*\right)
\end{aligned}$$

Now substitute into the time derivative of $\rho$:

$$\begin{aligned}
\frac{\partial \rho}{\partial t} &= \psi^* \cdot \frac{1}{i\hbar}\left(-\frac{\hbar^2}{2m}\frac{\partial^2 \psi}{\partial x^2} + V\psi\right) + \psi \cdot \left(-\frac{1}{i\hbar}\right)\left(-\frac{\hbar^2}{2m}\frac{\partial^2 \psi^*}{\partial x^2} + V\psi^*\right) \\
&= -\frac{\hbar}{2mi}\left(\psi^* \frac{\partial^2 \psi}{\partial x^2} - \psi \frac{\partial^2 \psi^*}{\partial x^2}\right)
\end{aligned}$$

Now observe the following identity (product rule):

$$\frac{\partial}{\partial x}\left(\psi^* \frac{\partial \psi}{\partial x} - \psi \frac{\partial \psi^*}{\partial x}\right) = \psi^* \frac{\partial^2 \psi}{\partial x^2} - \psi \frac{\partial^2 \psi^*}{\partial x^2}$$

Therefore:

$$\frac{\partial \rho}{\partial t} = -\frac{\hbar}{2mi}\frac{\partial}{\partial x}\left(\psi^* \frac{\partial \psi}{\partial x} - \psi \frac{\partial \psi^*}{\partial x}\right)$$

Define the probability current density $j(x,t)$ as:

$$j(x,t) = \frac{\hbar}{2mi}\left(\psi^* \frac{\partial \psi}{\partial x} - \psi \frac{\partial \psi^*}{\partial x}\right)$$

Then the continuity equation becomes:

$$\frac{\partial \rho}{\partial t} + \frac{\partial j}{\partial x} = 0$$

This is the continuity equation for probability, expressing conservation of probability in quantum mechanics.

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# Calculation of Dwell Time for a Rectangular Potential Barrier

## Definition of Dwell Time

Dwell time is defined as the average time a quantum particle spends inside a region (here, the potential barrier), regardless of whether it eventually transmits or reflects:

$$\tau_D = \frac{\int_{x_1}^{x_2} |\psi(x)|^2 \, dx}{j_{\text{in}}}$$

## Rectangular Potential Barrier

Let the potential be:

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

Assume $E < V_0$, so the particle undergoes tunneling. In the region $0 < x < a$, the wavefunction inside the barrier is:

$$\psi(x) = Ce^{-\kappa x} + De^{\kappa x}, \quad \text{where } \kappa = \sqrt{\frac{2m(V_0 - E)}{\hbar^2}}$$

In the typical tunneling case, we consider only the decaying exponential:

$$|\psi(x)|^2 = |C|^2 e^{-2\kappa x}$$

$$\int_0^a |\psi(x)|^2 \, dx = |C|^2 \int_0^a e^{-2\kappa x} dx = |C|^2 \cdot \frac{1 - e^{-2\kappa a}}{2\kappa}$$

In the region $x < 0$, if the incident wave is $\psi(x) = Ce^{ikx}$, then the incoming probability current is:

$$j_{\text{in}} = \frac{\hbar k}{m} |A|^2, \quad \text{where } k = \sqrt{\frac{2mE}{\hbar^2}}$$

Putting everything together:

$$\tau_D = \frac{|C|^2 \cdot \frac{1-e^{-2\kappa a}}{2\kappa}}{\frac{\hbar k}{m}|A|^2} = \left(\frac{m}{\hbar k}\right) \cdot \left(\frac{|C|^2}{|A|^2}\right) \cdot \left(\frac{1 - e^{-2\kappa a}}{2\kappa}\right)$$

The ratio $\frac{|c|^2}{|a|^2}$ can be determined from the continuity conditions at the boundaries of the potential. article amsmath physics

# Transmission Coefficient for a Finite Square Potential Barrier

For a particle with energy $E < V_0$, tunneling through a finite square barrier of height $V_0$ and width $a$, the transmission coefficient is given by:

$$T = \frac{1}{1 + \left(\frac{V_0^2}{4E(V_0 - E)}\right) \sinh^2(\kappa a)} \tag{4}$$