

## INFINITE SQUARE WELL - CUBIC SINE INITIAL STATE

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Post date: 9 Aug 2012.

Reference: Griffiths, David J. (2005), Introduction to Quantum Mechanics, 2nd Edition; Pearson Education - Problem 2.37.

As an example of the infinite square well potential suppose the particle starts off with the wave function

$$\Psi(x, 0) = A \sin^3\left(\frac{\pi x}{a}\right) \quad (1)$$

for  $0 \leq x \leq a$  (and zero elsewhere).

First, we can find  $A$  by normalizing (using software for the integral):

$$1 = |A|^2 \int_0^a \sin^6\left(\frac{\pi x}{a}\right) dx \quad (2)$$

$$= |A|^2 \frac{5}{16} a \quad (3)$$

$$A = \frac{4}{\sqrt{5a}} \quad (4)$$

The general solution as a function of time is the series

$$\Psi(x, t) = \sum_{n=1}^{\infty} c_n \Psi_n(x, t) \quad (5)$$

where  $\Psi_n$  are the stationary states of the square well. We find the  $c_n$  by considering the sum at  $t = 0$ :

$$\Psi(x, 0) = \sum_{n=1}^{\infty} c_n \Psi_n(x, 0) \quad (6)$$

$$= \sqrt{\frac{2}{a}} \sum_{n=1}^{\infty} c_n \sin\left(\frac{n\pi x}{a}\right) \quad (7)$$

Because the stationary states are orthogonal functions, we have

$$c_n = \sqrt{\frac{2}{a}} \int_0^a \sin\left(\frac{n\pi x}{a}\right) \Psi(x, 0) dx \quad (8)$$

$$= \sqrt{\frac{2}{a}} \frac{4}{\sqrt{5a}} \int_0^a \sin\left(\frac{n\pi x}{a}\right) \sin^3\left(\frac{\pi x}{a}\right) dx \quad (9)$$

$$= \frac{24}{5\pi} \frac{\sqrt{10} \sin(n\pi)}{n^4 - 10n^2 + 9} \quad (10)$$

A quick glance at this result might make you think that  $c_n = 0$  for all  $n$  because of the sine term. However, we need to be careful, since the denominator factors to

$$n^4 - 10n^2 + 9 = (n-1)(n+1)(n-3)(n+3) \quad (11)$$

and thus has zeroes at  $n = 1, 3$ . We can redo these integrals for these specific values of  $n$  and we get

$$c_1 = \sqrt{\frac{2}{a}} \frac{4}{\sqrt{5a}} \int_0^a \sin\left(\frac{\pi x}{a}\right) \sin^3\left(\frac{\pi x}{a}\right) dx \quad (12)$$

$$= \frac{3}{\sqrt{10}} \quad (13)$$

$$c_3 = \sqrt{\frac{2}{a}} \frac{4}{\sqrt{5a}} \int_0^a \sin\left(\frac{3\pi x}{a}\right) \sin^3\left(\frac{\pi x}{a}\right) dx \quad (14)$$

$$= -\frac{1}{\sqrt{10}} \quad (15)$$

The full solution is therefore

$$\Psi(x, t) = \frac{3}{\sqrt{5a}} \sin\left(\frac{\pi x}{a}\right) e^{-i\pi^2 \hbar t / 2ma^2} - \frac{1}{\sqrt{5a}} \sin\left(\frac{3\pi x}{a}\right) e^{-9i\pi^2 \hbar t / 2ma^2} \quad (16)$$

The particle will be found with energy  $E_1$  with probability of  $|c_1|^2 = 0.9$  and with energy  $E_3$  with probability 0.1. Thus

$$\langle E \rangle = (0.9 + 0.1 \times 3^2) \frac{\pi^2 \hbar^2}{2ma^2} \quad (17)$$

$$= 0.9 \frac{\pi^2 \hbar^2}{ma^2} \quad (18)$$

The mean position is found from

$$\langle x \rangle = \int_0^a x |\Psi(x,t)|^2 dx \quad (19)$$

Working out the integrand, we get

$$|\Psi(x,t)|^2 = -\frac{6}{5a} \sin\left(\frac{\pi x}{a}\right) \sin\left(\frac{3\pi x}{a}\right) \left( \sin\left(\frac{E_1 t}{\hbar}\right) \sin\left(\frac{E_3 t}{\hbar}\right) + \cos\left(\frac{E_1 t}{\hbar}\right) \cos\left(\frac{E_3 t}{\hbar}\right) \right) \quad (20)$$

$$+ \frac{2}{a} - \frac{9}{5a} \cos^2\left(\frac{\pi x}{a}\right) - \frac{1}{5a} \cos^2\left(\frac{3\pi x}{a}\right) \quad (21)$$

$$= -\frac{6}{5a} \sin\left(\frac{\pi x}{a}\right) \sin\left(\frac{3\pi x}{a}\right) \cos\left(\frac{(E_3 - E_1)t}{\hbar}\right) + \frac{2}{a} - \frac{9}{5a} \cos^2\left(\frac{\pi x}{a}\right) - \frac{1}{5a} \cos^2\left(\frac{3\pi x}{a}\right) \quad (22)$$

We can now do the integral using software with the result

$$\int_0^a x |\Psi(x,t)|^2 dx = \frac{a}{2} \quad (23)$$

The mean position is the midpoint of the well.