

# Relativistic Quantum Waves (Klein-Gordon Equation

Marcus Allen Denslow

2025-11-14

# Contents

## Chapter 1

### Deriving the KG Equation

Page 2

- 1.1 double deriving 2
- 1.2 Plugging in the new values 2
- 1.3 this is the Klein-Gordon Equation! 2
- 1.4 Replacing with Laplacian 3
- 1.5 d'Alembertian 3

## Chapter 2

### Four-momentum Eigenstates

Page 4

- 2.1 Klein-Gordon Plane Wave 4
- 2.2 Proof that plane waves  $\psi = A \exp [-ip \cdot x/\hbar]$  satisfy K.G. 4

# Chapter 1

## Deriving the KG Equation

### 1.1 double deriving

**Definition 1.1.1: Relativity: the mass shell**

$$p \cdot p = (mc)^2 \rightarrow (mc)^2 = \left(\frac{E}{c}\right)^2 - p_x^2 - p_y^2 - p_z^2$$

**Definition 1.1.2: Quantum: energy and momentum operators**

$$\hat{E} = i\hbar \frac{\partial}{\partial t}, \text{ so } \left(\frac{E}{c}\right)^2 \text{ becomes } -\frac{\hbar^2}{c^2} \frac{\partial^2}{\partial t^2}.$$

$$\hat{p} = -i\hbar \nabla, \text{ so } -p_x^2 \text{ becomes } \hbar^2 \frac{\partial^2}{\partial x^2}.$$

$$\text{likewise, } -p_y^2 \text{ becomes } \hbar^2 \frac{\partial^2}{\partial y^2} \text{ and } -p_z^2 \text{ becomes } \hbar^2 \frac{\partial^2}{\partial z^2}.$$

### 1.2 Plugging in the new values

we can now plugin these into the original equation:

$$\begin{aligned} (mc)^2 &= \left(\frac{E}{c}\right)^2 - p_x^2 - p_y^2 - p_z^2 \\ (mc)^2 &= -\frac{\hbar^2}{c^2} \frac{\partial^2}{\partial t^2} + \hbar^2 \frac{\partial^2}{\partial x^2} + \hbar^2 \frac{\partial^2}{\partial y^2} + \hbar^2 \frac{\partial^2}{\partial z^2} \\ \frac{1}{c^2} \frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial x^2} - \frac{\partial^2}{\partial y^2} - \frac{\partial^2}{\partial z^2} + \left(\frac{mc}{\hbar}\right)^2 &= 0. \end{aligned}$$

### 1.3 this is the Klein-Gordon Equation!

$$\frac{1}{c^2} \frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial x^2} - \frac{\partial^2}{\partial y^2} - \frac{\partial^2}{\partial z^2} + \left(\frac{mc}{\hbar}\right)^2 = 0 \quad (1.1)$$

$$\left[ \frac{1}{c^2} \frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial x^2} - \frac{\partial^2}{\partial y^2} - \frac{\partial^2}{\partial z^2} + \left(\frac{mc}{\hbar}\right)^2 \right] \psi = 0 \quad (1.2)$$

## 1.4 Replacing with Laplacian

We know that  $-\frac{\partial^2}{\partial x^2} - \frac{\partial^2}{\partial y^2} - \frac{\partial^2}{\partial z^2} = \nabla^2$  -otherwise known as a Laplacian

So the function becomes

$$\left[ \frac{1}{c^2} \frac{\partial^2}{\partial t^2} - \nabla^2 + \left( \frac{mc}{\hbar} \right)^2 \right] \psi = 0 \quad (1.3)$$

## 1.5 d'Alembertian

$\square =$  d'Alembertian

We can also rewrite  $\left( \frac{mc}{\hbar} \right)^2$  as  $\mu^2$

**Note:-**

We could also write  $\left( \frac{mc}{\hbar} \right)$  as just  $m$  as in this universe it would become  $\left( \frac{m \cdot 1}{1} \right)$  which is just the mass but this is the correct way to write it.

So our final equation becomes

$$[\square + \mu^2] \psi = 0 \quad (1.4)$$

## Chapter 2

# Four-momentum Eigenstates

### 2.1 Klein-Gordon Plane Wave

**Definition 2.1.1: Klein-Gorden Plane Wave function**

$$\psi = A \exp \left( -\frac{i}{\hbar} p \cdot x \right)$$

$$p = [E/c, \vec{p}] , \quad x = [ct, \vec{x}]$$

$$A \in \mathbb{C}, \quad p^0 = \frac{E}{c} = \pm \sqrt{|\vec{p}|^2 + m^2 c^2}$$

we can rewrite the original Equation as:

$$\psi = A \exp \left( \frac{i}{\hbar} (\vec{p} \cdot \vec{x} - Et) \right)$$

$$\psi = A \exp \left( \frac{i}{\hbar} \left( \vec{p} \cdot \vec{x} \pm c \sqrt{|\vec{p}|^2 + m^2 c^2} t \right) \right)$$

### 2.2 Proof that plane waves $\psi = A \exp \left[ -ip \cdot x / \hbar \right]$ satisfy K.G.