

(36.1) (a) Show that the Dirac equation can be recast in the form

$$i\frac{\partial\psi}{\partial t} = \hat{H}_D\psi \quad (36.33)$$

where $\hat{H}_D = \boldsymbol{\alpha} \cdot \hat{\mathbf{p}} + \beta m$ and find $\boldsymbol{\alpha}$ and β in terms of the γ matrices.

(b) Evaluate \hat{H}_D^2 and show that for a Klein-Gordon dispersion to result we must have:

- (i) that the α^i and β objects all anticommute with each other; and
- (ii) $(\alpha^i)^2 = (\beta)^2 = 1$.

(c) Prove the following commutation relations

- (i) $[\hat{H}, \hat{L}^i] = i(\hat{\mathbf{p}} \times \boldsymbol{\alpha})^i$ where $\hat{\mathbf{L}} = \hat{\mathbf{x}} \times \hat{\mathbf{p}}$.
- (ii) $[\hat{H}, \hat{S}^i] = -i(\hat{\mathbf{p}} \times \boldsymbol{\alpha})^i$ where $\hat{\mathbf{S}} = \frac{1}{2}\boldsymbol{\Sigma}$ and we define $\boldsymbol{\Sigma} = \frac{i}{2}\boldsymbol{\gamma} \times \boldsymbol{\gamma}$.

(a) Consider the following form of the Dirac equation.

$$i\left(\gamma^0\frac{\partial}{\partial t} + \gamma^1\frac{\partial}{\partial x} + \gamma^2\frac{\partial}{\partial y} + \gamma^3\frac{\partial}{\partial z}\right)\psi = m\psi$$

Rewrite as

$$i\gamma^0\frac{\partial}{\partial t}\psi = -i\left(\gamma^1\frac{\partial}{\partial x} + \gamma^2\frac{\partial}{\partial y} + \gamma^3\frac{\partial}{\partial z}\right)\psi + m\psi$$

Noting that $\gamma^0\gamma^0 = I$, multiply both sides by γ^0 to obtain

$$i\frac{\partial}{\partial t}\psi = -i\gamma^0\left(\gamma^1\frac{\partial}{\partial x} + \gamma^2\frac{\partial}{\partial y} + \gamma^3\frac{\partial}{\partial z}\right)\psi + m\gamma^0\psi$$

Hence for $\hat{\mathbf{p}} = -i\nabla$ we have

$$\boldsymbol{\alpha} = \gamma^0 \begin{pmatrix} \gamma^1 \\ \gamma^2 \\ \gamma^3 \end{pmatrix}, \quad \beta = \gamma^0$$

(b) (i) The dispersion relation is

$$\hat{H}_D^2 = \hat{\mathbf{p}}^2 + m^2$$

Squaring \hat{H}_D we have

$$\begin{aligned}\hat{H}_D^2 &= (\boldsymbol{\alpha} \cdot \hat{\mathbf{p}} + \beta m)(\boldsymbol{\alpha} \cdot \hat{\mathbf{p}} + \beta m) \\ &= (\boldsymbol{\alpha} \cdot \hat{\mathbf{p}})(\boldsymbol{\alpha} \cdot \hat{\mathbf{p}}) + (\boldsymbol{\alpha} \cdot \hat{\mathbf{p}})\beta m + \beta m(\boldsymbol{\alpha} \cdot \hat{\mathbf{p}}) + \beta^2 m^2\end{aligned}$$

The middle terms must cancel, that is

$$(\boldsymbol{\alpha} \cdot \hat{\mathbf{p}})\beta + \beta(\boldsymbol{\alpha} \cdot \hat{\mathbf{p}}) = 0$$

Hence

$$\alpha^i \beta = -\beta \alpha^i$$

Cross terms must cancel, that is

$$\left(-i\alpha^1 \frac{\partial}{\partial x} - i\alpha^2 \frac{\partial}{\partial y} - i\alpha^3 \frac{\partial}{\partial z}\right)^2 = -(\alpha^1)^2 \frac{\partial^2}{\partial x^2} - (\alpha^2)^2 \frac{\partial^2}{\partial y^2} - (\alpha^3)^2 \frac{\partial^2}{\partial z^2}$$

Hence

$$\alpha^i \alpha^j = -\alpha^j \alpha^i$$

(b) (ii) We now have

$$\hat{H}_D^2 = -(\alpha^1)^2 \frac{\partial^2}{\partial x^2} - (\alpha^2)^2 \frac{\partial^2}{\partial y^2} - (\alpha^3)^2 \frac{\partial^2}{\partial z^2} + \beta^2 m = \hat{\mathbf{p}}^2 + m^2$$

Hence

$$(\alpha^i)^2 = I \quad \text{and} \quad \beta^2 = I$$

(c) (i) In component form we have

$$\hat{\mathbf{p}} \times \boldsymbol{\alpha} = -i \begin{pmatrix} \frac{\partial}{\partial y} \alpha^3 - \frac{\partial}{\partial z} \alpha^2 \\ \frac{\partial}{\partial z} \alpha^1 - \frac{\partial}{\partial x} \alpha^3 \\ \frac{\partial}{\partial x} \alpha^2 - \frac{\partial}{\partial y} \alpha^1 \end{pmatrix}, \quad \hat{\mathbf{L}} = \hat{\mathbf{x}} \times \hat{\mathbf{p}} = -i \begin{pmatrix} y \frac{\partial}{\partial z} - z \frac{\partial}{\partial y} \\ z \frac{\partial}{\partial x} - x \frac{\partial}{\partial z} \\ x \frac{\partial}{\partial y} - y \frac{\partial}{\partial x} \end{pmatrix}$$

Noting that βm commutes with $\hat{\mathbf{L}}$ we have

$$[\hat{H}_D, \hat{\mathbf{L}}] = (\boldsymbol{\alpha} \cdot \hat{\mathbf{p}})(\hat{\mathbf{x}} \times \hat{\mathbf{p}}) - (\hat{\mathbf{x}} \times \hat{\mathbf{p}})(\boldsymbol{\alpha} \cdot \hat{\mathbf{p}})$$

By the product rule we have for $(\boldsymbol{\alpha} \cdot \hat{\mathbf{p}})(\hat{\mathbf{x}} \times \hat{\mathbf{p}})$ that

$$(\boldsymbol{\alpha} \cdot \hat{\mathbf{p}})(\hat{\mathbf{x}} \times \hat{\mathbf{p}}) = (\boldsymbol{\alpha} \cdot \hat{\mathbf{p}} \hat{\mathbf{x}}) \times \hat{\mathbf{p}} + \hat{\mathbf{x}} \times (\boldsymbol{\alpha} \cdot \hat{\mathbf{p}} \hat{\mathbf{p}})$$

By ordinary operator arithmetic $(\hat{\mathbf{x}} \times \hat{\mathbf{p}})(\boldsymbol{\alpha} \cdot \hat{\mathbf{p}})$ transforms as

$$(\hat{\mathbf{x}} \times \hat{\mathbf{p}})(\boldsymbol{\alpha} \cdot \hat{\mathbf{p}}) = \hat{\mathbf{x}} \times (\boldsymbol{\alpha} \cdot \hat{\mathbf{p}}\hat{\mathbf{p}})$$

Hence

$$[\hat{H}_D, \hat{\mathbf{L}}] = (\boldsymbol{\alpha} \cdot \hat{\mathbf{p}}\hat{\mathbf{x}}) \times \hat{\mathbf{p}} + \hat{\mathbf{x}} \times (\boldsymbol{\alpha} \cdot \hat{\mathbf{p}}\hat{\mathbf{p}}) - \hat{\mathbf{x}} \times (\boldsymbol{\alpha} \cdot \hat{\mathbf{p}}\hat{\mathbf{p}}) = (\boldsymbol{\alpha} \cdot \hat{\mathbf{p}}\hat{\mathbf{x}}) \times \hat{\mathbf{p}}$$

Noting that

$$\boldsymbol{\alpha} \cdot \hat{\mathbf{p}}\hat{\mathbf{x}} = \boldsymbol{\alpha} \cdot (-i\nabla\hat{\mathbf{x}}) = -i\boldsymbol{\alpha}$$

we have

$$[\hat{H}_D, \hat{\mathbf{L}}] = -i\boldsymbol{\alpha} \times \hat{\mathbf{p}} = i(\hat{\mathbf{p}} \times \boldsymbol{\alpha})$$