Quantum Mechanics

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A Modern Physics Review Clark Saben

Lecture 1: Quantum Mechanics I

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1.1 Representations of Spin Half

(a) Write $\hat{S}_z$ in the S_x basis, both in Dirac Notation and as a matrix. Hint: However you do this, you will need to know how $\hat{S}_z$ acts on the eignstates of S_x.

Find $\hat{S}_z$ in the S_x basis:

$$\hat{1}_x \hat{S}_z \hat{1}_x = (|+x\rangle\langle +x| + |-x\rangle\langle -x|)\, \hat{S}_z\, (|+x\rangle\langle +x| + |-x\rangle\langle -x|)$$

Need $\hat{S}_z$ (hint):

$$\begin{aligned} \hat{1}_z|\pm x\rangle &= |+z\rangle\langle +z|\pm x\rangle + |-z\rangle\langle -z|\pm x\rangle \\ &= \frac{1}{\sqrt{2}}\left(|+z\rangle| \pm |-z\rangle\right) \\ \Rightarrow \hat{S}_z|\pm x\rangle &= \frac{\hbar}{2\sqrt{2}}\left(\langle +z| \pm \langle -z|\right) \end{aligned}$$

So,

$$\begin{aligned} \hat{1}_x \hat{S}_z \hat{1}_x &= (|+x\rangle\langle +x| + |-x\rangle\langle -x|)\left(\frac{\hbar}{2}|-x\rangle\langle +x| + \frac{\hbar}{2}|+x\rangle\langle -x|\right) \\ &= \frac{\hbar}{2}\left(|+x\rangle\langle -x| + |-x\rangle\langle +x|\right) \end{aligned}$$

$$\Rightarrow \mathbb{S}_z^{(S_x)} = \frac{\hbar}{2}\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

(b) Verify the equations (in the S_x basis),
using your matrix representation for $\hat{S}_z$ in the S_x basis.

$$\hat{S}_z|\pm z\rangle = \pm\frac{\hbar}{2}|\pm z\rangle$$

$$\begin{aligned}
\mathbb{S}_z^{(S_x)}\vec{v}_{+z}^{(S_x)} &= \frac{\hbar}{2\sqrt{2}}\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}\begin{pmatrix} 1 \\ 1 \end{pmatrix} \\
&= \frac{\hbar}{2\sqrt{2}}\begin{pmatrix} 1 \\ 1 \end{pmatrix} \\
&= \frac{\hbar}{2}\begin{pmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{pmatrix} \\
&= \frac{\hbar}{2}\vec{v}_{+z}^{(S_x)}
\end{aligned}$$

$$\hat{1}_x|-z\rangle = |+x\rangle\langle +x|-z\rangle + |-x\rangle\langle -x|-z\rangle$$

where

$$\langle +x|-z\rangle = \frac{1}{\sqrt{2}}$$

and

$$\langle -x|-z\rangle = \frac{-1}{\sqrt{2}}$$

$$\begin{aligned}
\Rightarrow \mathbb{S}_z^{(S_x)}\vec{v}_{-z}^{(S_x)} &= \frac{\hbar}{2\sqrt{2}}\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}\begin{pmatrix} 1 \\ -1 \end{pmatrix} \\
&= \frac{\hbar}{2\sqrt{2}}\begin{pmatrix} -1 \\ 1 \end{pmatrix} \\
&= \frac{-\hbar}{2}\begin{pmatrix} \frac{1}{\sqrt{2}} \\ \frac{-1}{\sqrt{2}} \end{pmatrix} \\
&= \frac{-\hbar}{2}\vec{v}_{-z}^{(S_x)}
\end{aligned}$$

(c) Write the projection operator $\hat{P}_{+z}$ in the S_x basis, both in Dirac Notation and as a matrix.

Find $\hat{P}_{+z}^{(S_x)}$ and $\hat{P}_{+z}$ in the S_x basis:

$$\begin{aligned}
\hat{P}_{+z}^{(S_x)} &= \hat{1}_x \hat{P}_{+z} \hat{1}_x \\
&= (|+x\rangle\langle +x| + |-x\rangle\langle -x|) \left(\frac{1}{\sqrt{2}} |+z\rangle\langle +x| + \frac{1}{\sqrt{2}} |+z\rangle\langle -x| \right) \\
&= \frac{1}{2} (|+x\rangle\langle +x| + |+x\rangle\langle -x| + |-x\rangle\langle +x| + |-x\rangle\langle -x|)
\end{aligned}$$

$$\mathbb{P}_{+z}^{(S_x)} = \frac{1}{2} \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$$

(d) Find eigenvalues and eigenvectors of your matrix representation of $\hat{P}_{+z}$ in the S_x basis, thus verifying that $\hat{P}_{+z}|+z\rangle = |+z\rangle$.

Diagnolize $\mathbb{P}_{+z}^{(S_x)}$ and verify $\mathbb{P}_{+z}^{S_x} \vec{v}_{+z}^{S_x} = \vec{v}_{+z}^{S_x}$.

$$\lambda_1 \lambda_2 = 0 \; ; \; \lambda_1 + \lambda_2 = 1$$
$$\Rightarrow \lambda_1 = 1 \text{ and } \lambda_2 = 0$$

$$\begin{pmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} \end{pmatrix} \begin{pmatrix} a \\ b \end{pmatrix} = \begin{pmatrix} a \\ b \end{pmatrix}$$

(e) Repeat parts (c) and (d) for $\hat{P}_{-z}$.