

## Two spins

Spin state  $|s\rangle$  for two spins is a unit vector in  $\mathbb{C}^4$ .

$$|s\rangle = \begin{pmatrix} c_{++} \\ c_{+-} \\ c_{-+} \\ c_{--} \end{pmatrix}, \quad |c_{++}|^2 + |c_{+-}|^2 + |c_{-+}|^2 + |c_{--}|^2 = 1$$

Spin measurement probabilities are the transition probabilities from  $|s\rangle$  to an eigenstate.

For spin measurements in the  $z$  direction we have

$$\begin{aligned} \Pr(S_{1z} = +\frac{\hbar}{2} \text{ and } S_{2z} = +\frac{\hbar}{2}) &= |\langle z_{++}|s\rangle|^2 = |c_{++}|^2 \\ \Pr(S_{1z} = +\frac{\hbar}{2} \text{ and } S_{2z} = -\frac{\hbar}{2}) &= |\langle z_{+-}|s\rangle|^2 = |c_{+-}|^2 \\ \Pr(S_{1z} = -\frac{\hbar}{2} \text{ and } S_{2z} = +\frac{\hbar}{2}) &= |\langle z_{-+}|s\rangle|^2 = |c_{-+}|^2 \\ \Pr(S_{1z} = -\frac{\hbar}{2} \text{ and } S_{2z} = -\frac{\hbar}{2}) &= |\langle z_{--}|s\rangle|^2 = |c_{--}|^2 \end{aligned}$$

where the eigenstates are

$$z_{++} = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}, \quad z_{+-} = \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix}, \quad z_{-+} = \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \end{pmatrix}, \quad z_{--} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix}$$

Operators for the first spin ( $\otimes$  is kronecker product):

$$\begin{aligned} S_{1x} &= \frac{\hbar}{2} \sigma_x \otimes I = \frac{\hbar}{2} \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} \\ S_{1y} &= \frac{\hbar}{2} \sigma_y \otimes I = \frac{\hbar}{2} \begin{pmatrix} 0 & 0 & -i & 0 \\ 0 & 0 & 0 & -i \\ i & 0 & 0 & 0 \\ 0 & i & 0 & 0 \end{pmatrix} \\ S_{1z} &= \frac{\hbar}{2} \sigma_z \otimes I = \frac{\hbar}{2} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \end{aligned}$$

Operators for the second spin:

$$\begin{aligned}
S_{2x} &= \frac{\hbar}{2} I \otimes \sigma_x = \frac{\hbar}{2} \begin{pmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix} \\
S_{2y} &= \frac{\hbar}{2} I \otimes \sigma_y = \frac{\hbar}{2} \begin{pmatrix} 0 & -i & 0 & 0 \\ i & 0 & 0 & 0 \\ 0 & 0 & 0 & -i \\ 0 & 0 & i & 0 \end{pmatrix} \\
S_{2z} &= \frac{\hbar}{2} I \otimes \sigma_z = \frac{\hbar}{2} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}
\end{aligned}$$

Expectation values for the first spin:

$$\begin{aligned}
\langle S_{1x} \rangle &= \langle s | S_{1x} | s \rangle = \frac{\hbar}{2} (c_{++}c_{-+}^* + c_{++}^*c_{-+} + c_{+-}c_{--}^* + c_{+-}^*c_{--}) \\
\langle S_{1y} \rangle &= \langle s | S_{1y} | s \rangle = \frac{i\hbar}{2} (c_{++}c_{+-}^* - c_{++}^*c_{+-} + c_{+-}c_{--}^* - c_{+-}^*c_{--}) \\
\langle S_{1z} \rangle &= \langle s | S_{1z} | s \rangle = \frac{\hbar}{2} (|c_{++}|^2 + |c_{+-}|^2 - |c_{-+}|^2 - |c_{--}|^2)
\end{aligned}$$

Expectation values for the second spin:

$$\begin{aligned}
\langle S_{2x} \rangle &= \langle s | S_{2x} | s \rangle = \frac{\hbar}{2} (c_{++}c_{+-}^* + c_{++}^*c_{+-} + c_{-+}c_{--}^* + c_{-+}^*c_{--}) \\
\langle S_{2y} \rangle &= \langle s | S_{2y} | s \rangle = \frac{i\hbar}{2} (c_{++}c_{+-}^* - c_{++}^*c_{+-} + c_{-+}c_{--}^* - c_{-+}^*c_{--}) \\
\langle S_{2z} \rangle &= \langle s | S_{2z} | s \rangle = \frac{\hbar}{2} (|c_{++}|^2 - |c_{+-}|^2 + |c_{-+}|^2 - |c_{--}|^2)
\end{aligned}$$

Expected spin vectors:

$$\langle \mathbf{S}_1 \rangle = \langle s | \mathbf{S}_1 | s \rangle = \begin{pmatrix} \langle S_{1x} \rangle \\ \langle S_{1y} \rangle \\ \langle S_{1z} \rangle \end{pmatrix}, \quad \langle \mathbf{S}_2 \rangle = \langle s | \mathbf{S}_2 | s \rangle = \begin{pmatrix} \langle S_{2x} \rangle \\ \langle S_{2y} \rangle \\ \langle S_{2z} \rangle \end{pmatrix}$$

Consider the case of having determined  $\langle \mathbf{S}_1 \rangle$  and  $\langle \mathbf{S}_2 \rangle$  by experiment. To convert  $\langle \mathbf{S}_1 \rangle$  and  $\langle \mathbf{S}_2 \rangle$  to a spin state  $|s\rangle$ , let

$$\begin{aligned}
x_i &= \frac{2}{\hbar} \langle S_{ix} \rangle = \sin \theta_i \cos \phi_i \\
y_i &= \frac{2}{\hbar} \langle S_{iy} \rangle = \sin \theta_i \sin \phi_i \\
z_i &= \frac{2}{\hbar} \langle S_{iz} \rangle = \cos \theta_i
\end{aligned}$$

Then

$$|s_i\rangle = \begin{pmatrix} \cos(\theta_i/2) \\ \sin(\theta_i/2) \exp(i\phi_i) \end{pmatrix}$$

where

$$\begin{aligned} \cos(\theta_i/2) &= \sqrt{\frac{\cos \theta_i + 1}{2}} = \sqrt{\frac{z_i + 1}{2}} \\ \sin(\theta_i/2) &= \sqrt{\frac{1 - \cos \theta_i}{2}} = \sqrt{\frac{1 - z_i}{2}} \end{aligned}$$

and

$$\exp(i\phi_i) = \cos \phi_i + i \sin \phi_i = \frac{x_i + iy_i}{\sqrt{x_i^2 + y_i^2}}$$

Spin state  $|s\rangle$  is the kronecker product of  $|s_1\rangle$  and  $|s_2\rangle$ .

$$|s\rangle = |s_1\rangle \otimes |s_2\rangle$$

Spin total angular momentum magnitude squared operator  $(\mathbf{S}_1 + \mathbf{S}_2)^2$ .

$$(\mathbf{S}_1 + \mathbf{S}_2)^2 = (S_{1x} + S_{2x})^2 + (S_{1y} + S_{2y})^2 + (S_{1z} + S_{2z})^2 = \hbar^2 \begin{pmatrix} 2 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 2 \end{pmatrix}$$

Expectation value for  $(\mathbf{S}_1 + \mathbf{S}_2)^2$ .

$$\langle s | (\mathbf{S}_1 + \mathbf{S}_2)^2 | s \rangle = \hbar^2 (2|c_{++}|^2 + |c_{+-} + c_{-+}|^2 + 2|c_{--}|^2)$$

## Exercises

1. Verify spin operators for two spins.
2. Verify expectation values for two spins.
3. Let

$$|s_1\rangle = \begin{pmatrix} \cos(\theta_1/2) \\ \sin(\theta_1/2) \exp(i\phi_1) \end{pmatrix}, \quad |s_2\rangle = \begin{pmatrix} \cos(\theta_2/2) \\ \sin(\theta_2/2) \exp(i\phi_2) \end{pmatrix}$$

and

$$|s\rangle = |s_1\rangle \otimes |s_2\rangle$$

Verify that

$$\langle s | \mathbf{S}_1 | s \rangle = \frac{\hbar}{2} \begin{pmatrix} \sin \theta_1 \cos \phi_1 \\ \sin \theta_1 \sin \phi_1 \\ \cos \theta_1 \end{pmatrix}, \quad \langle s | \mathbf{S}_2 | s \rangle = \frac{\hbar}{2} \begin{pmatrix} \sin \theta_2 \cos \phi_2 \\ \sin \theta_2 \sin \phi_2 \\ \cos \theta_2 \end{pmatrix}$$

4. Verify that for a product state  $|s\rangle = |s_1\rangle \otimes |s_2\rangle$  we have

$$\langle S_{1j} S_{2k} \rangle = \langle S_{1j} \rangle \langle S_{2k} \rangle$$

where  $j, k \in \{x, y, z\}$ .