

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

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

Spin operators for the first spin (\otimes is kronecker product).

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

Spin 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.

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

Total spin operator.

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

Expectation value for total spin.

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

Exercises

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