

Exercise 6.10. A system of two spins has the Hamiltonian

$$\mathbf{H} = \frac{\omega}{2} \vec{\sigma} \cdot \vec{\tau}$$

What are the possible energies of the system, and what are the eigenvectors of the Hamiltonian?

Suppose the system starts in the state  $|uu\rangle$ . What is the state at any later time? Answer the same question for initial states of  $|ud\rangle$ ,  $|du\rangle$ , and  $|dd\rangle$ .

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Consider equation (4.28).

$$\mathbf{H}|E_j\rangle = E_j|E_j\rangle \quad (4.28)$$

By (4.28) the possible energies are the eigenvalues of  $\mathbf{H}$ . From Exercise 6.9 the eigenvalues of  $\vec{\sigma} \cdot \vec{\tau}$  are  $-3$  and  $1$ . Hence the possible energies are  $-3\omega/2$  and  $\omega/2$ . Also from Exercise 6.9 the eigenvectors are  $|sing\rangle$ ,  $|T_1\rangle$ ,  $|T_2\rangle$ , and  $|T_3\rangle$ .

Without using Exercise 6.9 we have

$$\mathbf{H} = \frac{\omega}{2} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 2 & 0 \\ 0 & 2 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

The characteristic polynomial of  $\mathbf{H}$  is

$$|\mathbf{H} - \lambda \mathbf{I}| = \lambda^4 - \frac{3}{2}\lambda^2\omega^2 + \lambda\omega^3 - \frac{3}{16}\omega^4 = 0$$

The roots of the characteristic polynomial are  $\lambda = -3\omega/2$  and  $\lambda = \omega/2$ . These  $\lambda$  are the eigenvalues of  $\mathbf{H}$  and hence the possible energies.

Consider equation (4.30).

$$\alpha_j(t) = \alpha_j(0) \exp\left(-\frac{iE_j t}{\hbar}\right) \quad (4.30)$$

Note that  $|uu\rangle$  and  $|dd\rangle$  are eigenvectors of  $\mathbf{H}$ .

$$\begin{aligned}\mathbf{H}|uu\rangle &= \frac{\omega}{2} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 2 & 0 \\ 0 & 2 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} = \frac{\omega}{2}|uu\rangle \\ \mathbf{H}|dd\rangle &= \frac{\omega}{2} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 2 & 0 \\ 0 & 2 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} = \frac{\omega}{2}|dd\rangle\end{aligned}$$

By (4.30) with  $E_{uu} = E_{dd} = \omega/2$  we have

$$\begin{aligned}|\Psi_{uu}(t)\rangle &= \exp\left(-\frac{i\omega t}{2\hbar}\right)|uu\rangle \\ |\Psi_{dd}(t)\rangle &= \exp\left(-\frac{i\omega t}{2\hbar}\right)|dd\rangle\end{aligned}$$

For the initial state  $|ud\rangle$  we have

$$|ud\rangle = \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix} = \frac{1}{\sqrt{2}}|T_1\rangle + \frac{1}{\sqrt{2}}|sing\rangle$$

By equation (4.30) with  $E_{T_1} = \omega/2$  and  $E_{sing} = -3\omega/2$  we have

$$|\Psi_{ud}(t)\rangle = \frac{1}{\sqrt{2}} \exp\left(-\frac{i\omega t}{2\hbar}\right)|T_1\rangle + \frac{1}{\sqrt{2}} \exp\left(\frac{3i\omega t}{2\hbar}\right)|sing\rangle$$

For the initial state  $|du\rangle$  we have

$$|du\rangle = \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \end{pmatrix} = \frac{1}{\sqrt{2}}|T_1\rangle - \frac{1}{\sqrt{2}}|sing\rangle$$

By equation (4.30) with  $E_{T_1} = \omega/2$  and  $E_{sing} = -3\omega/2$  we have

$$|\Psi_{du}(t)\rangle = \frac{1}{\sqrt{2}} \exp\left(-\frac{i\omega t}{2\hbar}\right)|T_1\rangle - \frac{1}{\sqrt{2}} \exp\left(\frac{3i\omega t}{2\hbar}\right)|sing\rangle$$