ROTATION OF A VECTOR WAVE FUNCTION

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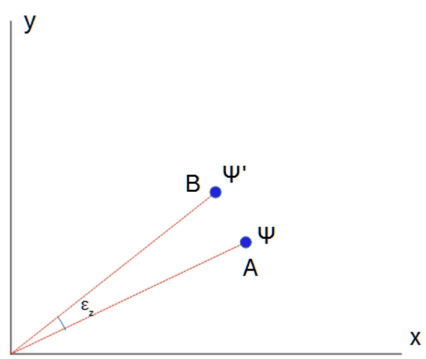
Shankar, R. (1994), *Principles of Quantum Mechanics*, Plenum Press. Chapter 12, Exercise 12.5.1.

[If some equations are too small to read easily, use your browser's magnifying option (Ctrl + on Chrome, probably something similar on other browsers).]

We've seen that, for a rotation by an infinitesimal angle ε_z about the z axis, a scalar wave function transforms according to

$$\psi(x,y) \rightarrow \psi(x+\varepsilon_z y, y-\varepsilon_z x) \tag{0.1}$$

The meaning of this transformation can be seen in the figure:



The physical system represented by the wave function Ψ is rigidly rotated by the angle ε_z, so that the value of Ψ at point A is now sitting over the point B. However, in the primed (rotated) coordinate system, the numerical value of the coordinates of the point B in the figure are the same as the numerical values that the point A had in the original, unrotated coordinates. That is

$$\left(x'_B, y'_B\right) = (x_A, y_A) \tag{0.2}$$

Just as B is obtained from A by rotating A by $+\varepsilon_z$, we can obtain A from B by rotating by $-\varepsilon_z$. For any given point, the primed (rotated) and unprimed (unrotated) coordinates are related by (all relations are to first order in ε_z):

$$x' = x - y\varepsilon_z \tag{0.3}$$
$$y' = y + x\varepsilon_z \tag{0.4}$$

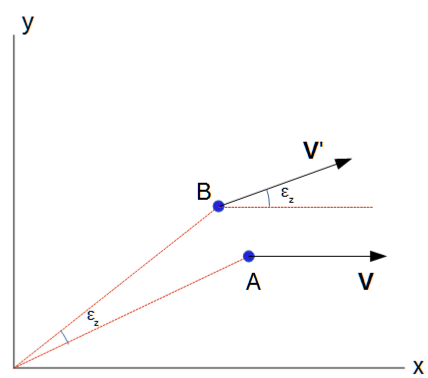
The inverse relations are obtained by a rotation by $-\varepsilon_z$:

$$x = x' + y'\varepsilon_z \tag{0.5}$$
$$y = y' - x'\varepsilon_z \tag{0.6}$$

After rotation, the values of Ψ' are related to the values Ψ before rotation by rotating through the angle $-\varepsilon_z$, so that

$$\Psi'(x,y) = \Psi(x + y\varepsilon_z, y - x\varepsilon_z) \tag{0.7}$$

Now suppose the wave function is a vector $\mathbf{V} = V_x\hat{\mathbf{x}} + V_y\hat{\mathbf{y}}$. The situation is as shown:



The initial unrotated vector $\mathbf{V}$ is the value of the wave function at point A (and is entirely in the x direction for convenience). After rotation, the vector gets moved to B and is also rotated so that it now makes an angle ε_z with the *original* x axis. However, its direction is now along the x' axis, which makes an angle of ε_z with the original x axis.

In this case, each component of $\mathbf{V}$ still gets transformed in the same way as the scalar function above, but the vector itself is also rotated. If the components V_x and V_y of the vector were constants, then the rotated vector is given by applying the 2-d rotation matrix

$$R = \begin{bmatrix} 1 & -\varepsilon_z \\ \varepsilon_z & 1 \end{bmatrix} \tag{0.8}$$

so we get $\mathbf{V}' = R\mathbf{V}$, or, in components:

$$V_x' = V_x - V_y\varepsilon_z \tag{0.9}$$
$$V_y' = V_y + V_x\varepsilon_z \tag{0.10}$$

If V_x and V_y vary from point to point, then we must apply the transformation 0.1 to each component, so that the overall transformation is

$$V_x' = V_x\left(x+\varepsilon_z y, y-\varepsilon_z x\right) - V_y\left(x+\varepsilon_z y, y-\varepsilon_z x\right)\varepsilon_z \tag{0.11}$$
$$V_y' = V_y\left(x+\varepsilon_z y, y-\varepsilon_z x\right) + V_x\left(x+\varepsilon_z y, y-\varepsilon_z x\right)\varepsilon_z \tag{0.12}$$

The operator that generates the transformation of a scalar function by an infinitesimal angle $\delta\theta$ is

$$U\left[R\left(\delta\theta\right)\right] = I - \frac{i}{\hbar}\delta\theta\cdot\mathbf{L} \tag{0.13}$$

In this case, the rotation is about the z axis so

$$\delta\theta = \varepsilon_z\hat{\mathbf{z}} \tag{0.14}$$
$$\delta\theta\cdot\mathbf{L} = \varepsilon_z L_z \tag{0.15}$$

Thus we have

$$V_{x,y}\left(x+\varepsilon_z y, y-\varepsilon_z x\right) = \left(I - \frac{i}{\hbar}\varepsilon_z L_z\right)V_{x,y}\left(x,y\right) \tag{0.16}$$

Plugging this into 0.11 and keeping terms only up to order ε_z we have

$$V_x' = \left(I - \frac{i}{\hbar}\varepsilon_z L_z\right)V_x - V_y\varepsilon_z \tag{0.17}$$
$$V_y' = \left(I - \frac{i}{\hbar}\varepsilon_z L_z\right)V_y + V_x\varepsilon_z \tag{0.18}$$

In matrix form, this is

$$\begin{bmatrix} V_x' \\ V_y' \end{bmatrix} = \left(\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} - \frac{i\varepsilon_z}{\hbar}\begin{bmatrix} L_z & 0 \\ 0 & L_z \end{bmatrix} - \varepsilon_z\begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}\right)\begin{bmatrix} V_x \\ V_y \end{bmatrix} \tag{0.19}$$
$$= \left(\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} - \frac{i\varepsilon_z}{\hbar}\begin{bmatrix} L_z & 0 \\ 0 & L_z \end{bmatrix} - \frac{i\varepsilon_z}{\hbar}\begin{bmatrix} 0 & -i\hbar \\ i\hbar & 0 \end{bmatrix}\right)\begin{bmatrix} V_x \\ V_y \end{bmatrix} \tag{0.20}$$
$$= \left(I - \frac{i\varepsilon_z}{\hbar}J_z\right)\begin{bmatrix} V_x \\ V_y \end{bmatrix} \tag{0.21}$$

This has the same form as 0.13, except that the angular momentum generator is now the sum of L_z and the final matrix on the RHS above, which Shankar calls suggestively S_z, in anticipation of spin which at this stage he hasn't considered. That is,

$$J_z = L_z + S_z \tag{0.22}$$

$$= \left[\begin{array}{cc} L_z & 0 \\ 0 & L_z \end{array}\right] + \left[\begin{array}{cc} 0 & -i\hbar \\ i\hbar & 0 \end{array}\right] \tag{0.23}$$

The eigenvalues of the second matrix here are just $\pm\hbar$, so we haven't yet encountered half-integral values of angular momentum.

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