Physics 570A Lecture 23

Angular Momentum

To treat problems with rotational symmetry, it is useful to introduce the angular momentum operator $\vec{L} = \vec{r} \times \vec{p}$.

$$\vec{L} = \begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ x & y & z \\ p_x & p_y & p_z \end{vmatrix}$$

$$L_x = y p_z - z p_y$$

$$L_y = z p_x - x p_z$$

$$L_z = x p_y - y p_x$$

$\vec{L}$ is a Hermitian operator,

$\vec{L}^{\dagger} = \vec{L}$. For example,

$$L_z^{\dagger} = p_y^{\dagger} x^{\dagger} - p_x^{\dagger} y^{\dagger} = p_y x - p_x y$$
$$= x p_y - y p_x = L_z$$

Here, we have used

$$[r_i, p_j] = i\hbar \delta_{ij} \qquad i, j = 1, 2, 3$$

$$\vec{r} = (r_1, r_2, r_3) = (x, y, z)$$

$$\vec{p} = (p_1, p_2, p_3) = (p_x, p_y, p_z)$$

Example $\quad [x, p_y] = 0$

$$[x, p_y]\psi(x, y, z) = \frac{\hbar}{i}\left(x \frac{\partial \psi}{\partial y} - \frac{\partial}{\partial y}(x\psi)\right)$$
$$= 0$$

An essential property of the angular momentum operator is that its components do not commute with one another:

$$[L_x, L_y] = [yP_z - zP_y, zP_x - xP_z]$$

$$= [yP_z, zP_x] + [zP_y, xP_z]$$

$$= y[P_z, z]P_x + x[z, P_z]P_y$$

$$= i\hbar(xP_y - yP_x) = i\hbar L_z$$

In general,

$$[L_i, L_j] = i\hbar\, \varepsilon_{ijk} L_k ,$$

where ε_{ijk} is the antisymmetric unit tensor:

$$\varepsilon_{123} = \varepsilon_{312} = \varepsilon_{231} = 1$$

$$\varepsilon_{ijk} = -\varepsilon_{jik} = -\varepsilon_{ikj}.$$

In other words,

$$[L_y, L_z] = i\hbar L_x$$

$$[L_z, L_x] = i\hbar L_y.$$

Another way to express these commutation relations is

$$\vec{L} \times \vec{L} = i\hbar \vec{L}$$

(note that the cross-product would be zero for ordinary vectors).

The commutation relations imply uncertainty relations, e.g.

$$\Delta L_x \, \Delta L_y \geq \frac{\hbar}{2} |\langle L_z \rangle| .$$

These uncertainty relations imply that it is impossible to know simultaneously two different components of the $\vec{L}$ (unless $\langle \vec{L} \rangle = 0$, the trivial case).

However, each component of $\vec{L}$ commutes with $\vec{L}^2$:

$$[\vec{L}^2, L_i] = 0 .$$

$$\vec{L}^2 = L_x^2 + L_y^2 + L_z^2$$

$$[\vec{L}^2, L_z] = [L_x^2, L_z] + [L_y^2, L_z]$$

$$= L_x [L_x, L_z] + [L_x, L_z] L_x$$
$$+ L_y [L_y, L_z] + [L_y, L_z] L_y$$

$$= -i\hbar (L_x L_y + L_y L_x)$$
$$+ i\hbar (L_y L_x + L_x L_y) = 0$$

and similarly for L_x and ~~L_y~~.

Thus we can characterize <u>angular momentum eigenfunctions</u> in terms of the eigenvalues of $\vec{L}^2$ and any one component, say L_z:

$$\vec{L}^2 \Psi_{\lambda m} = \lambda \Psi_{\lambda m}$$

$$L_z \Psi_{\lambda m} = m\hbar \Psi_{\lambda m}$$

The operator method for angular momentum

Define two new operators

$$L_+ = L_x + i L_y$$

$$L_- = L_x - i L_y = L_+^\dagger$$

Clearly $[\vec{L}^2, L_\pm] = 0.$

$$[L_z, L_+] = [L_z, L_x + i L_y]$$
$$= i\hbar L_y + i(-i\hbar L_x)$$
$$= \hbar(L_x + i L_y) = \hbar L_+$$

$$[L_z, L_-] = i\hbar L_y - \hbar L_x = -\hbar L_-$$

$$[L_+, L_-] = [L_x + iL_y, L_x - iL_y]$$
$$= -i[L_x, L_y] + i[L_y, L_x]$$
$$= 2\hbar L_z$$

Furthermore,

$$L_+L_- = (L_x + iL_y)(L_x - iL_y)$$
$$= L_x^2 + L_y^2 - i[L_x, L_y]$$
$$= L_x^2 + L_y^2 + \hbar L_z$$

$$L_-L_+ = L_x^2 + L_y^2 + i[L_x, L_y]$$
$$= L_x^2 + L_y^2 - \hbar L_z$$

$$\Rightarrow \vec{L}^2 = \frac{1}{2}(L_+L_- + L_-L_+) + L_z^2$$

From the commutator, we have

$$L_z L_+ = L_+(L_z + \hbar)$$

$$L_z(L_+ \psi_{\lambda m}) = L_+(L_z + \hbar)\psi_{\lambda m}$$
$$= (m+1)\hbar\,(L_+ \psi_{\lambda m})$$

$\Rightarrow$ $L_+ \psi_{\lambda m}$ is an eigenstate of L_z with eigenvalue $(m+1)\hbar$. Similarly,

$$L_z L_- \psi_{\lambda m} = (m-1)\hbar\, L_- \psi_{\lambda m}$$

L_+ and L_- are known as <u>raising</u> and <u>lowering operators</u>.

$$\vec{L}^2 L_\pm \psi_{\lambda m} = L_\pm \vec{L}^2 \psi_{\lambda m} = \lambda L_\pm \psi_{\lambda m}$$

Thus $L_\pm \psi_{\lambda m}$ is an eigenstate of $\vec{L}^2$ with the same eigenvalue λ. $L_\pm$ increase/decrease L_z, but leave $\vec{L}^2$ unchanged.

Normalization

$$L_\pm \Psi_{\lambda m} = \alpha_\pm \Psi_{\lambda, m\pm 1}$$

Find $\alpha_\pm$.

$$L_+ \Psi_{\lambda m} = \alpha_+ \Psi_{\lambda m+1}$$

$$\langle L_+ \Psi_{\lambda m} | L_+ \Psi_{\lambda m} \rangle = |\alpha_+|^2 \underbrace{\langle \Psi_{\lambda m+1} | \Psi_{\lambda m+1} \rangle}_{=1}$$

simplify notation

$$\langle \Psi_{\lambda m} | L_- L_+ \Psi_{\lambda m} \rangle \equiv \langle \lambda m | L_- L_+ | \lambda m \rangle$$

$$= |\alpha_+|^2$$

$$|\alpha_+|^2 = \langle \lambda m | \vec{L}^2 - L_z^2 - \hbar L_z | \lambda m \rangle$$

$$= \lambda - \hbar^2 m(m+1)$$

$$\boxed{\begin{aligned} &\Rightarrow \quad L_+ \psi_{\lambda m} = \sqrt{\lambda - \hbar^2 m(m+1)}\ \psi_{\lambda\, m+1} \\ &\text{also} \quad L_- \psi_{\lambda m} = \sqrt{\lambda - \hbar^2 m(m-1)}\ \psi_{\lambda\, m-1} \end{aligned}}$$

Now $\vec{L}^2 = L_x^2 + L_y^2 + L_z^2$

$$\lambda = \langle \lambda m | \vec{L}^2 | \lambda m \rangle = \langle \lambda m | L_x^2 + L_y^2 | \lambda m \rangle + m^2 \hbar^2$$

$$\Rightarrow \quad \lambda \geq m^2 \hbar^2$$

since $\langle J_i^2 \rangle \geq 0$ for any hermitian operator J_i.

$$|m| \leq \sqrt{\lambda/\hbar^2}$$

$$-\sqrt{\lambda/\hbar^2} \leq m \leq \sqrt{\lambda/\hbar^2}$$

But for any particular value of m, we can always generate $m \pm 1$ by using the raising or lowering operator. We cannot keep doing so ad infinitum. We must have

$$L_+ \psi_{\lambda m_{max}} = 0$$

$$\Rightarrow \quad \lambda = \hbar^2 m_{max} (m_{max} + 1)$$

and $\quad L_- \psi_{\lambda m_{min}} = 0$

$$\Rightarrow \quad \lambda = \hbar^2 m_{min} (m_{min} - 1).$$

Furthermore,

$$m_{max} - m_{min} = n \geq 0,$$

where $n \in \mathbb{Z}$ is the number

of times we must apply L_+ to $\psi_{\lambda m_{min}}$ to generate $\psi_{\lambda m_{max}}$.

The only possible solution is

$$m_{max} - m_{min} = n \equiv 2\ell$$

$$\lambda = \hbar^2 \ell(\ell+1)$$

$$-\ell \leq m \leq \ell \qquad (2\ell+1 \text{ values})$$

Rewrite $\psi_{\lambda m} \equiv \psi_{\ell m}$

$$\boxed{\begin{aligned} \vec{L}^2 \psi_{\ell m} &= \hbar^2 \ell(\ell+1)\, \psi_{\ell m} \\ L_z \psi_{\ell m} &= m\hbar\, \psi_{\ell m} \\ L_\pm \psi_{\ell m} &= \hbar\sqrt{\ell(\ell+1) - m(m\pm 1)}\; \psi_{\ell m\pm 1} \end{aligned}}$$

As we shall see, for orbital angular momentum $\vec{L} = \vec{r} \times \vec{p}$, the quantum number

$$\ell = \text{integer.}$$

However, the angular momentum algebra only requires

$$n = 2\ell = \text{integer.}$$

Half-odd integers arise from "spin," the intrinsic angular momentum of certain elementary particles, which has no classical analogue — or from a combination of spin and orbital angular momentum.

"Vector model" for eigenstates of $\vec{L}^2$, L_z

$$\vec{L}^2 \psi_{\ell m} = \hbar^2 \ell(\ell+1) \psi_{\ell m}$$

$$L_z \psi_{\ell m} = \hbar m \psi_{\ell m}$$

$$L_z^2 \psi_{\ell m} = (\hbar m)^2 \psi_{\ell m}$$

$$(L_x^2 + L_y^2) \psi_{\ell m} = (\vec{L}^2 - L_z^2) \psi_{\ell m}$$

$$= \hbar^2 (\ell(\ell+1) - m^2) \psi_{\ell m}$$

$\Rightarrow$ The wavefunction $\psi_{\ell m}$ has definite values of $\vec{L}^2$, L_z, and $L_x^2 + L_y^2$. L_x and L_y individually are uncertain, because

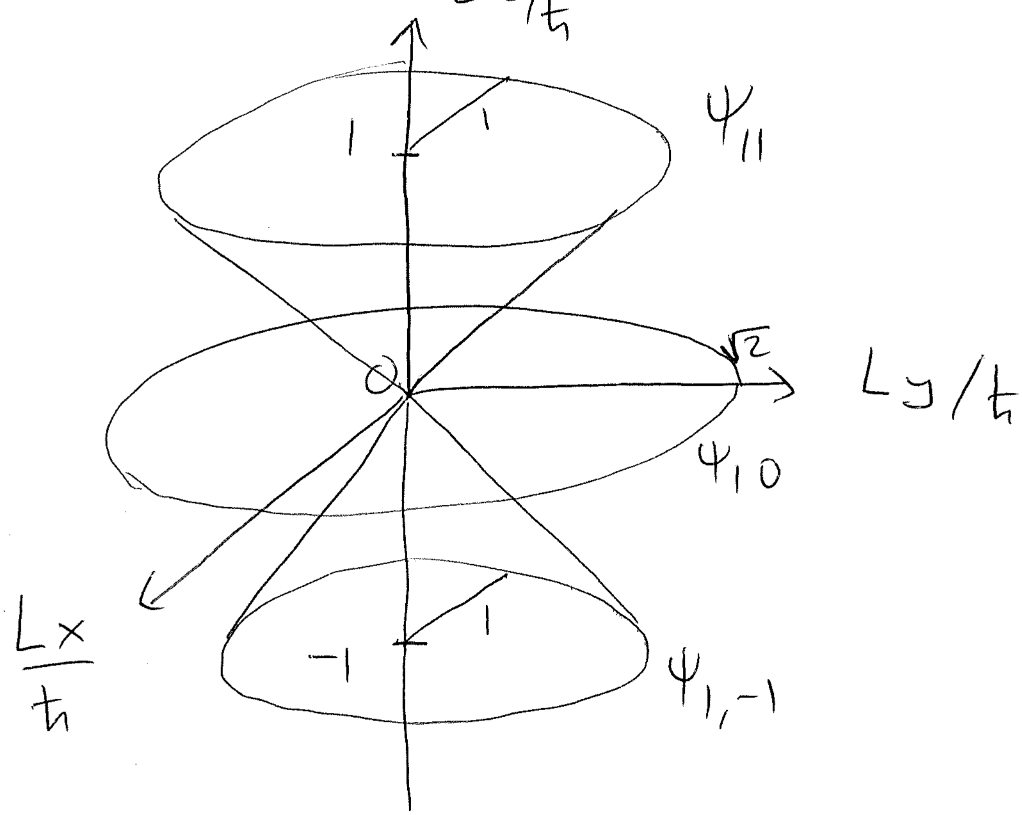
$$\Delta L_x \Delta L_y \geq \frac{\hbar}{2} |\langle L_z \rangle|.$$

Example 1 $\quad \ell = 1, \quad m = -1, 0, 1$

$$\ell(\ell+1) = 2$$

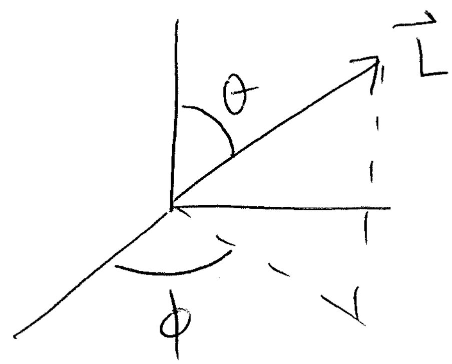
$$(L_x^2 + L_y^2)\,\psi_{1,\pm1} = \hbar^2 (2-1)\,\psi_{1,\pm1}$$
$$= \hbar^2\,\psi_{1,\pm1}$$

$$(L_x^2 + L_y^2)\,\psi_{10} = 2\hbar^2\,\psi_{10}$$



$m=0$: $\vec{L}$ lies in x-y plane

$m=\pm1$: $\vec{L}$ lies on upper (lower) cone



θ known

φ uncertain

Example 2 $\quad l = 0 \,, \quad m = 0$

$$L_x = L_y = L_z = 0$$

Example 3 $\quad l = \frac{1}{2} \equiv s \quad$ (spin)

$$m = -\frac{1}{2}, \frac{1}{2} \,, \qquad 2s+1 = 2$$

$$\vec{S}^2 = \hbar^2 s(s+1) = \frac{3}{4}\hbar^2$$

$$\left(S_x^2 + S_y^2\right)\psi_{\frac{1}{2},\pm\frac{1}{2}} = \left(\vec{S}^2 - S_z^2\right)\psi_{\frac{1}{2},\pm\frac{1}{2}}$$

$$= \hbar^2 \frac{1}{2} \, \psi_{\frac{1}{2},\pm\frac{1}{2}}$$