To summarize,

$|\uparrow_1 \uparrow_2\rangle$ has eigenvalue of $\underset{\sim}{\vec{S}_1} \cdot \underset{\sim}{\vec{S}_2} = \frac{\hbar^2}{4}$

$\frac{1}{\sqrt{2}}(|\uparrow_1 \downarrow_2\rangle + |\downarrow_1 \uparrow_2\rangle)$ " "

$|\downarrow_1 \downarrow_2\rangle$ " "

$\frac{1}{\sqrt{2}}(|\uparrow_1 \downarrow_2\rangle - |\downarrow_1 \uparrow_2\rangle)$ " $= -3\frac{\hbar^2}{4}$

Another way of looking at this is to consider the operators: (Read Text 107-113)

$$\underset{\sim}{\vec{S}}^2 \equiv (\underset{\sim}{\vec{S}_1} + \underset{\sim}{\vec{S}_2})^2 = \underset{\sim}{\vec{S}_1}^2 + \underset{\sim}{\vec{S}_2}^2 + 2\underset{\sim}{\vec{S}_1} \cdot \underset{\sim}{\vec{S}_2}$$

$$\underset{\sim}{\vec{S}_1}^2 |\uparrow_1 \uparrow_2\rangle = \hbar^2 \cdot \tfrac{1}{2}(\tfrac{1}{2}+1)|\uparrow_1 \uparrow_2\rangle = \tfrac{3}{4}\hbar^2 |\uparrow_1 \uparrow_2\rangle$$

same for $|\uparrow_1 \downarrow_2\rangle, |\downarrow_1 \uparrow_2\rangle, |\downarrow_1 \downarrow_2\rangle$; $\underset{\sim}{\vec{S}_2}^2$

so

$$\underset{\sim}{\vec{S}}^2 \begin{bmatrix} |\uparrow_1 \uparrow_2\rangle \\ \frac{1}{\sqrt{2}}(|\uparrow_1 \downarrow_2\rangle + |\downarrow_1 \uparrow_2\rangle) \\ |\downarrow_1 \downarrow_2\rangle \end{bmatrix} = \underbrace{\Big(\overset{\vec{S}_1^2 + \vec{S}_2^2}{2 \times \tfrac{3}{4}\hbar^2} + \overset{+2\vec{S}_1 \cdot \vec{S}_2}{2 \times \tfrac{\hbar^2}{4}}\Big)}_{1(1+1)\hbar^2} \begin{bmatrix} |\uparrow_1 \uparrow_2\rangle \\ \frac{1}{\sqrt{2}}(|\uparrow_1 \downarrow_2\rangle + |\downarrow_1 \uparrow_2\rangle) \\ |\downarrow_1 \downarrow_2\rangle \end{bmatrix}$$

so the <u>triplet</u> of states has total angular momentum $1 \times \hbar$; eigenvalue of $\underset{\sim}{\vec{S}}^2$ is $S(S+1)\hbar^2$, so $S=1$

the z-component of $\underset{\sim}{\vec{S}}$ varies for these 3 states varies:

$$\underset{\sim}{S_z}|\uparrow_1 \uparrow_2\rangle = (\underset{\sim}{S_{1z}} + \underset{\sim}{S_{2z}})|\uparrow_1 \uparrow_2\rangle = (\tfrac{\hbar}{2} + \tfrac{\hbar}{2})|\uparrow_1 \uparrow_2\rangle = \hbar|\uparrow_1 \uparrow_2\rangle; \quad S_z = 1$$

$$\underset{\sim}{S_z}\tfrac{1}{\sqrt{2}}(|\uparrow_1 \downarrow_2\rangle + |\downarrow_1 \uparrow_2\rangle) = (\underset{\sim}{S_{1z}} + \underset{\sim}{S_{2z}})\tfrac{1}{\sqrt{2}}(|\uparrow_1 \downarrow_2\rangle + |\downarrow_1 \uparrow_2\rangle) = (\tfrac{\hbar}{2} - \tfrac{\hbar}{2})\tfrac{1}{\sqrt{2}}(|\uparrow_1 \downarrow_2\rangle + |\downarrow_1 \uparrow_2\rangle)$$

$S_z = 0$

and $\underset{\sim}{S_z}|\downarrow_1 \downarrow_2\rangle = -\hbar|\downarrow_1 \downarrow_2\rangle \quad S_z = -1$

For the <u>singlet</u>

$$\underset{\sim}{\vec{S}}^2 \left[\tfrac{1}{\sqrt{2}}(|\uparrow_1 \downarrow_2\rangle - |\downarrow_1 \uparrow_2\rangle)\right] = \Big(\overset{\vec{S}_1^2 + \vec{S}_2^2}{2 \times \tfrac{3}{4}\hbar^2} \overset{+2\vec{S}_2 \cdot \vec{S}_1}{- 2\tfrac{3}{4}\hbar^2}\Big)\tfrac{1}{\sqrt{2}}(|\uparrow_1 \downarrow_2\rangle - |\downarrow_1 \uparrow_2\rangle)$$

$$= 0 \times \tfrac{1}{\sqrt{2}}(|\uparrow_1 \downarrow_2\rangle - |\downarrow_1 \uparrow_2\rangle)$$

so: eigenvalue of $\underset{\sim}{\vec{S}}^2$ is $0 \cdot \hbar^2$, or $S = 0$, $\underset{\sim}{S_z}$ is 0

What's happened here is an example of the <u>addition</u> of angular momentum. The addition of angular momentum $\vec{J}_1$ and $\vec{J}_2$ (which might be 2 spins; an orbital + a spin; or even 2 orbitals) is relevant <u>when</u> there is physics that adds a term like $\vec{J}_1 \cdot \vec{J}_2$ to the Hamiltonian

Eigenvalues of $(\vec{J}_1 + \vec{J}_2)^2 = \vec{J}_1^2 + \vec{J}_2^2 + 2\vec{J}_1 \cdot \vec{J}_2$

"total angular momentum"

will be eigenvalues of $\vec{J}_1 \cdot \vec{J}_2$.

So there are two bases:

#1 Product States:

$|j_1 j_2 m_1 m_2\rangle$

eigenstates of of $\vec{J}_1^2, \vec{J}_2^2, J_{1z}, J_{2z}$

$\boxed{\text{like } |\uparrow_1 \downarrow_2\rangle}$

not eigenstates of $(\vec{J}_1 + \vec{J}_2)^2$

#2 Eigenstates of Total J

$|j_1 j_2 J M\rangle$

eigenstates of $\vec{J}_1^2, \vec{J}_2^2, J_{1z} + J_{2z}$, $\vec{J}^2 = (\vec{J}_1 + \vec{J}_2)^2$

not eigenstates of individually J_{1z} J_{2z}

like $\frac{1}{\sqrt{2}}(|\uparrow_1 \downarrow_2\rangle \pm |\downarrow_1 \uparrow_2\rangle)$

$\boxed{\text{How Many ??}}$

Product states: $-j_1 \le m_1 \le +j_1$ $\quad -j_2 \le m_2 \le j_2$

$\# = (2j_1 + 1) \times (2j_2 + 1)$

Eigenstates of total J $\quad \# = ?$

<u>answer</u>: $|j_1 - j_2| \le J \le j_1 + j_2$

Claim: $\sum_{j=|j_1-j_2|}^{j_1+j_2} (2j+1) = (2j_1+1)(2j_2+1)$

homework.

The coefficients that translate between the $|j_1 j_2 m_1 m_2\rangle$ basis and the $|j_1 j_2 J M\rangle$ are known as the "Clebsch-Gordan" coefficients

$$|j_1 j_2 m_1 m_2\rangle = \sum_{J=|j_1-j_2|}^{j_1+j_2} \underset{\uparrow}{C^{J\, j_1\, j_2}_{M\, m_1\, m_2}} |j_1 j_2 J M\rangle$$

Coefficients $\qquad M = m_1 + m_2$

example: $j_1 = 2,\ j_2 = 1 \Rightarrow 1 \le J \le 3$

$m_1 = 1 \quad m_2 = -1$

$$\boxed{|21;\underbrace{1\,{-1}}_{M=0}\rangle = \sqrt{\tfrac{1}{5}}\,|21;3\,0\rangle + \sqrt{\tfrac{1}{2}}\,|21;2\,0\rangle + \sqrt{\tfrac{3}{10}}\,|21;1\,0\rangle}$$

reverse works as well.

$$|j_1 j_2 J M\rangle = \sum_{\substack{m_1, m_2 \\ m_1+m_2=M}} C^{J\, j_1\, j_2}_{M\, m_1\, m_2} |j_1 j_2 m_1 m_2\rangle$$

again: $j_1 = 2,\ j_2 = 1 \qquad 1 \le J \le 3$

pick $J = 2,\ M = 0$

$$\boxed{|2\ 0\rangle = \sqrt{\tfrac{1}{2}}\,|21;1\,{-1}\rangle + 0\,|21;0\,0\rangle - \sqrt{\tfrac{1}{2}}\,|21;{-1}\,1\rangle}$$

use particle data book table (attached) to get the C-G coefficients

31. CLEBSCH-GORDAN COEFFICIENTS, SPHERICAL HARMONICS, AND d FUNCTIONS

Note: A square-root sign is to be understood over *every* coefficient, *e.g.*, for −8/15 read $-\sqrt{8/15}$.

Notation:

		J	J	...
		M	M	...
m_1	m_2	Coefficients		
m_1	m_2			
.	.			
.	.			

1/2×1/2

		1
		+1
+1/2	+1/2	1

		1	0
		0	0
+1/2	−1/2	1/2	1/2
−1/2	+1/2	1/2	−1/2

		1
		−1
−1/2	−1/2	1

1×1/2

		3/2
		+3/2
+1	+1/2	1

		3/2	1/2
		+1/2	+1/2
+1	−1/2	1/3	2/3
0	+1/2	2/3	−1/3

		3/2	1/2
		−1/2	−1/2
0	−1/2	2/3	1/3
−1	+1/2	1/3	−2/3

		3/2
		−3/2
−1	−1/2	1

2×1

		3
		+3
+2	+1	1

		3	2
		+2	+2
+2	0	1/3	2/3
+1	+1	2/3	−1/3

		3	2	1
		+1	+1	+1
+2	−1	1/15	1/3	3/5
+1	0	8/15	1/6	−3/10
0	+1	2/5	−1/2	1/10

		3	2	1
		0	0	0
+1	−1	1/5	1/2	3/10
0	0	3/5	0	−2/5
−1	+1	1/5	−1/2	3/10

		3	2	1
		−1	−1	−1
0	−1	2/5	1/2	1/10
−1	0	8/15	−1/6	−3/10
−2	+1	1/15	−1/3	3/5

		3	2
		−2	−2
−1	−1	2/3	1/3
−2	0	1/3	−2/3

		3
		−3
−2	−1	1

1×1

		2
		+2
+1	+1	1

		2	1
		+1	+1
+1	0	1/2	1/2
0	+1	1/2	−1/2

		2	1	0
		0	0	0
+1	−1	1/6	1/2	1/3
0	0	2/3	0	−1/3
−1	+1	1/6	−1/2	1/3

		2	1
		−1	−1
0	−1	1/2	1/2
−1	0	1/2	−1/2

		2
		−2
−1	−1	1

$$Y_1^0 = \sqrt{\frac{3}{4\pi}}\cos\theta$$

$$Y_1^1 = -\sqrt{\frac{3}{8\pi}}\sin\theta\, e^{i\phi}$$

$$Y_2^0 = \sqrt{\frac{5}{4\pi}}\Big(\frac{3}{2}\cos^2\theta - \frac{1}{2}\Big)$$

$$Y_2^1 = -\sqrt{\frac{15}{8\pi}}\sin\theta\cos\theta\, e^{i\phi}$$

$$Y_2^2 = \frac{1}{4}\sqrt{\frac{15}{2\pi}}\sin^2\theta\, e^{2i\phi}$$

$$Y_\ell^{-m} = (-1)^m Y_\ell^{m*}$$

$$d^{\,\ell}_{m,0} = \sqrt{\frac{4\pi}{2\ell+1}}\, Y_\ell^m\, e^{-im\phi}$$

2×1/2

		5/2
		+5/2
+2	+1/2	1

		5/2	3/2
		+3/2	+3/2
+2	−1/2	1/5	4/5
+1	+1/2	4/5	−1/5

		5/2	3/2
		+1/2	+1/2
+1	−1/2	2/5	3/5
0	+1/2	3/5	−2/5

		5/2	3/2
		−1/2	−1/2
0	−1/2	3/5	2/5
−1	+1/2	2/5	−3/5

		5/2	3/2
		−3/2	−3/2
−1	−1/2	4/5	1/5
−2	+1/2	1/5	−4/5

		5/2
		−5/2
−2	−1/2	1

3/2×1/2

		2
		+2
+3/2	+1/2	1

		2	1
		+1	+1
+3/2	−1/2	1/4	3/4
+1/2	+1/2	3/4	−1/4

		2	1
		0	0
+1/2	−1/2	1/2	1/2
−1/2	+1/2	1/2	−1/2

		2	1
		−1	−1
−1/2	−1/2	3/4	1/4
−3/2	+1/2	1/4	−3/4

		2
		−2
−3/2	−1/2	1

3/2×1

		5/2
		+5/2
+3/2	+1	1

		5/2	3/2
		+3/2	+3/2
+3/2	0	2/5	3/5
+1/2	+1	3/5	−2/5

		5/2	3/2	1/2
		+1/2	+1/2	+1/2
+3/2	−1	1/10	2/5	1/2
+1/2	0	3/5	1/15	−1/3
−1/2	+1	3/10	−8/15	1/6

		5/2	3/2	1/2
		−1/2	−1/2	−1/2
+1/2	−1	3/10	8/15	1/6
−1/2	0	3/5	−1/15	−1/3
−3/2	+1	1/10	−2/5	1/2

		5/2	3/2
		−3/2	−3/2
−1/2	−1	3/5	2/5
−3/2	0	2/5	−3/5

		5/2
		−5/2
−3/2	−1	1

$$\langle j_1 j_2 m_1 m_2 | j_1 j_2 J M\rangle = (-1)^{J-j_1-j_2}\langle j_2 j_1 m_2 m_1 | j_2 j_1 J M\rangle$$

$$d^{\,j}_{m',m} = (-1)^{m-m'} d^{\,j}_{m,m'} = d^{\,j}_{-m,-m'}$$

2×3/2

		7/2
		+7/2
+2	+3/2	1

		7/2	5/2
		+5/2	+5/2
+2	+1/2	3/7	4/7
+1	+3/2	4/7	−3/7

		7/2	5/2	3/2
		+3/2	+3/2	+3/2
+2	−1/2	1/7	16/35	2/5
+1	+1/2	4/7	1/35	−2/5
0	+3/2	2/7	−18/35	1/5

		7/2	5/2	3/2	1/2
		+1/2	+1/2	+1/2	+1/2
+2	−3/2	1/35	6/35	2/5	2/5
+1	−1/2	12/35	5/14	0	−3/10
0	+1/2	18/35	−3/35	−1/5	1/5
−1	+3/2	4/35	−27/70	2/5	−1/10

		7/2	5/2	3/2	1/2
		−1/2	−1/2	−1/2	−1/2
+1	−3/2	4/35	27/70	2/5	1/10
0	−1/2	18/35	3/35	−1/5	−1/5
−1	+1/2	12/35	−5/14	0	3/10
−2	+3/2	1/35	−6/35	2/5	−2/5

		7/2	5/2	3/2
		−3/2	−3/2	−3/2
0	−3/2	2/7	18/35	1/5
−1	−1/2	4/7	−1/35	−2/5
−2	+1/2	1/7	−16/35	2/5

		7/2	5/2
		−5/2	−5/2
−1	−3/2	4/7	3/7
−2	−1/2	3/7	−4/7

		7/2
		−7/2
−2	−3/2	1

3/2×3/2

		3
		+3
+3/2	+3/2	1

		3	2
		+2	+2
+3/2	+1/2	1/2	1/2
+1/2	+3/2	1/2	−1/2

		3	2	1
		+1	+1	+1
+3/2	−1/2	1/5	1/2	3/10
+1/2	+1/2	3/5	0	−2/5
−1/2	+3/2	1/5	−1/2	3/10

		3	2	1	0
		0	0	0	0
+3/2	−3/2	1/20	1/4	9/20	1/4
+1/2	−1/2	9/20	1/4	−1/20	−1/4
−1/2	+1/2	9/20	−1/4	−1/20	1/4
−3/2	+3/2	1/20	−1/4	9/20	−1/4

		3	2	1
		−1	−1	−1
+1/2	−3/2	1/5	1/2	3/10
−1/2	−1/2	3/5	0	−2/5
−3/2	+1/2	1/5	−1/2	3/10

		3	2
		−2	−2
−1/2	−3/2	1/2	1/2
−3/2	−1/2	1/2	−1/2

		3
		−3
−3/2	−3/2	1

$$d^{\,1}_{0,0} = \cos\theta \qquad d^{\,1/2}_{1/2,1/2} = \cos\frac{\theta}{2} \qquad d^{\,1}_{1,1} = \frac{1+\cos\theta}{2}$$

$$d^{\,1/2}_{1/2,-1/2} = -\sin\frac{\theta}{2} \qquad d^{\,1}_{1,0} = -\frac{\sin\theta}{\sqrt{2}}$$

$$d^{\,1}_{1,-1} = \frac{1-\cos\theta}{2}$$

2×2

		4
		+4
+2	+2	1

		4	3
		+3	+3
+2	+1	1/2	1/2
+1	+2	1/2	−1/2

		4	3	2
		+2	+2	+2
+2	0	3/14	1/2	2/7
+1	+1	4/7	0	−3/7
0	+2	3/14	−1/2	2/7

		4	3	2	1
		+1	+1	+1	+1
+2	−1	1/14	3/10	3/7	1/5
+1	0	3/7	1/5	−1/14	−3/10
0	+1	3/7	−1/5	−1/14	3/10
−1	+2	1/14	−3/10	3/7	−1/5

		4	3	2	1	0
		0	0	0	0	0
+2	−2	1/70	1/10	2/7	2/5	1/5
+1	−1	8/35	2/5	1/14	−1/10	−1/5
0	0	18/35	0	−2/7	0	1/5
−1	+1	8/35	−2/5	1/14	1/10	−1/5
−2	+2	1/70	−1/10	2/7	−2/5	1/5

		4	3	2	1
		−1	−1	−1	−1
+1	−2	1/14	3/10	3/7	1/5
0	−1	3/7	1/5	−1/14	−3/10
−1	0	3/7	−1/5	−1/14	3/10
−2	+1	1/14	−3/10	3/7	−1/5

		4	3	2
		−2	−2	−2
0	−2	3/14	1/2	2/7
−1	−1	4/7	0	−3/7
−2	0	3/14	−1/2	2/7

		4	3
		−3	−3
−1	−2	1/2	1/2
−2	−1	1/2	−1/2

		4
		−4
−2	−2	1

$$d^{\,3/2}_{3/2,3/2} = \frac{1+\cos\theta}{2}\cos\frac{\theta}{2}$$

$$d^{\,3/2}_{3/2,1/2} = -\sqrt{3}\,\frac{1+\cos\theta}{2}\sin\frac{\theta}{2} \qquad d^{\,2}_{2,2} = \Big(\frac{1+\cos\theta}{2}\Big)^2$$

$$d^{\,3/2}_{3/2,-1/2} = \sqrt{3}\,\frac{1-\cos\theta}{2}\cos\frac{\theta}{2} \qquad d^{\,2}_{2,1} = -\frac{1+\cos\theta}{2}\sin\theta$$

$$d^{\,3/2}_{3/2,-3/2} = -\frac{1-\cos\theta}{2}\sin\frac{\theta}{2} \qquad d^{\,2}_{2,0} = \frac{\sqrt{6}}{4}\sin^2\theta \qquad d^{\,2}_{1,1} = \frac{1+\cos\theta}{2}(2\cos\theta - 1)$$

$$d^{\,3/2}_{1/2,1/2} = \frac{3\cos\theta - 1}{2}\cos\frac{\theta}{2} \qquad d^{\,2}_{2,-1} = -\frac{1-\cos\theta}{2}\sin\theta \qquad d^{\,2}_{1,0} = -\sqrt{\frac{3}{2}}\sin\theta\cos\theta$$

$$d^{\,3/2}_{1/2,-1/2} = -\frac{3\cos\theta + 1}{2}\sin\frac{\theta}{2} \qquad d^{\,2}_{2,-2} = \Big(\frac{1-\cos\theta}{2}\Big)^2 \qquad d^{\,2}_{1,-1} = \frac{1-\cos\theta}{2}(2\cos\theta + 1) \qquad d^{\,2}_{0,0} = \Big(\frac{3}{2}\cos^2\theta - \frac{1}{2}\Big)$$

Figure 31.1: The sign convention is that of Wigner (*Group Theory*, Academic Press, New York, 1959), also used by Condon and Shortley (*The Theory of Atomic Spectra*, Cambridge Univ. Press, New York, 1953), Rose (*Elementary Theory of Angular Momentum*, Wiley, New York, 1957), and Cohen (*Tables of the Clebsch-Gordan Coefficients*, North American Rockwell Science Center, Thousand Oaks, Calif., 1974). The coefficients here have been calculated using computer programs written independently by Cohen and at LBNL.