5.1. İki tane spini 1/2 olan parçacık ele alalım. Örneğin taban durumunda bulunan Hidrojen atomundaki elektron ve proton gibi. Toplam açısal momentum nedir?

$S^{(1)} = 1/2 \; ; \; m_{s1} = 1/2, -1/2$

$S^{(2)} = 1/2 \; ; \; m_{s2} = 1/2, -1/2$

$S = S^{(1)} + S^{(2)} \rightarrow S = |s_1 - s_2| \ldots (s_1 + s_2) \rightarrow S = 1, 0$

$|s_1, m_{s1}; s_2, m_{s2}\rangle \Rightarrow$

$|s_1, m_{s1}\rangle |s_2, m_{s2}\rangle$

$|1/2, 1/2; 1/2, 1/2\rangle = |\uparrow\uparrow\rangle \quad m=1$

$|1/2, 1/2; 1/2, -1/2\rangle = |\uparrow\downarrow\rangle \quad m=0$

$|1/2, -1/2; 1/2, 1/2\rangle = |\downarrow\uparrow\rangle \quad m=0$

$|1/2, -1/2; 1/2, -1/2\rangle = |\downarrow\downarrow\rangle \quad \underbrace{m=-1}_{S_z}$

Elde edilen dört tane karma durumun her biri S_z'nin özdurumudur;

- $S_z \underbrace{|1/2, 1/2\rangle}_{s_1 \; m_{s1}} \underbrace{|1/2, 1/2\rangle}_{s_2 \; m_{s2}} = (S_z^{(1)} + S_z^{(2)}) |1/2, 1/2\rangle |1/2, 1/2\rangle$

$$= \underbrace{(S_z^{(1)} |1/2\, 1/2\rangle)}_{\frac{1}{2}\hbar |1/2\, 1/2\rangle} |1/2, 1/2\rangle + |1/2\, 1/2\rangle \underbrace{(S_z^{(2)} |1/2, 1/2\rangle)}_{1/2\hbar |1/2\, 1/2\rangle}$$

$$= \frac{\hbar}{2} |1/2\, 1/2\rangle |1/2\, 1/2\rangle + \frac{\hbar}{2} |1/2\, 1/2\rangle |1/2\, 1/2\rangle$$

$$= \left(\frac{\hbar}{2} + \frac{\hbar}{2}\right) |1/2\, 1/2\rangle |1/2\, 1/2\rangle$$

$$= \hbar |1/2\, 1/2\rangle |1/2, 1/2\rangle, \quad m = m_{s1} + m_{s2} = 1\hbar$$

- $S_z \underbrace{|1/2, 1/2\rangle}_{|\uparrow\rangle,\; m_{s1} = 1/2} \underbrace{|1/2, -1/2\rangle}_{|\downarrow\rangle,\; m_{s2} = -1/2} = (S_z^{(1)} + S_z^{(2)}) |\uparrow\rangle |\downarrow\rangle$

$$= \underbrace{(S_z^{(1)} |\uparrow\rangle)}_{\frac{\hbar}{2} |\uparrow\rangle} |\downarrow\rangle + |\uparrow\rangle \underbrace{(S_z^{(2)} |\downarrow\rangle)}_{-\frac{\hbar}{2} |\downarrow\rangle}$$

$$= \left(\frac{\hbar}{2} - \frac{\hbar}{2}\right) |\uparrow\rangle |\downarrow\rangle$$

$$= 0\hbar \, |\uparrow\rangle |\downarrow\rangle \quad m = m_{s1} + m_{s2} = 0$$

- $S_z \underbrace{|1/2, -1/2\rangle}_{|\downarrow\rangle} \underbrace{|1/2, 1/2\rangle}_{|\uparrow\rangle} = (S_z^{(1)} + S_z^{(2)}) |\downarrow\rangle |\uparrow\rangle$

$$= (S_z^{(1)} |\downarrow\rangle) |\uparrow\rangle + |\downarrow\rangle (S_z^{(2)} |\uparrow\rangle)$$

$$= \left(-\frac{\hbar}{2} + \frac{\hbar}{2}\right) |\downarrow\rangle |\uparrow\rangle$$

$$= 0\hbar \, |\downarrow\rangle |\uparrow\rangle \quad m = m_{s1} + m_{s2} = 0$$

- $S_z \underbrace{|1/2, -1/2\rangle}_{|\downarrow\rangle} \underbrace{|1/2, -1/2\rangle}_{|\downarrow\rangle} = (S_z^{(1)} |\downarrow\rangle) |\downarrow\rangle + |\downarrow\rangle (S_z^{(2)} |\downarrow\rangle)$

$$= \left(-\frac{\hbar}{2} - \hbar/2\right) |\downarrow\rangle |\downarrow\rangle$$

$$= -\hbar \, |\downarrow\rangle |\downarrow\rangle \quad m = m_{s1} + m_{s2} = -\hbar$$

Kuantum Fiziği 2 Uygulama Notları
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Bu yazdıklarımız ilk bakışta doğru gözükmüyor! Çünkü m'in +s'den −s'ye tamsayı adımlarla ilerlemesi beklenir. Böylece s=1 durumu elde edilir. Ancak m=0 olan "fazladan" bir durum daha vardır. Bu sorunu çözmek için $|\uparrow\rangle|\uparrow\rangle$ durumuna S_- operatörünü uygulayalım;

$$S_\mp |s, m_s\rangle = \hbar\sqrt{s(s+1) - m_s(m_s \mp 1)}\; |s, m_s \mp 1\rangle$$

- $$S_- \underbrace{|1/2\ 1/2\rangle}_{|\uparrow\rangle} \underbrace{|1/2\ 1/2\rangle}_{|\uparrow\rangle} = (S_-^{(1)} + S_-^{(2)})\,|1/2, 1/2\rangle|1/2\ 1/2\rangle$$

$|s\, m_s\rangle = |1, 1\rangle$ (s^T, m_s toplam)

$$= \Big[\underbrace{S_-^{(1)} |1/2\ 1/2\rangle}_{\hbar\sqrt{\frac{1}{2}(\frac{1}{2}+1) - \frac{1}{2}(\frac{1}{2}-1)}\,|\frac{1}{2}, -1/2\rangle \;=\; \hbar\,|1/2\ -1/2\rangle}\Big]|1/2\ 1/2\rangle + |1/2\ 1/2\rangle\Big[\underbrace{S_-^{(2)}|1/2\ 1/2\rangle}_{\hbar\,|1/2, -1/2\rangle}\Big]$$

$$= \hbar\,|1/2\ -1/2\rangle|1/2\ 1/2\rangle + \hbar\,|1/2\ 1/2\rangle|1/2\ -1/2\rangle$$

$$= \hbar\Big[|1/2, -1/2\rangle|1/2\ 1/2\rangle + |1/2\ 1/2\rangle|1/2\ -1/2\rangle\Big]$$

$$S_-|1\ 1\rangle = \hbar\Big[|\downarrow\rangle|\uparrow\rangle + |\uparrow\rangle|\downarrow\rangle\Big]$$

$|s, m_s\rangle$

$$\left.\begin{aligned} |1,1\rangle &= |\uparrow\rangle|\uparrow\rangle \\ |1,0\rangle &= \frac{1}{\sqrt{2}}\Big[|\uparrow\rangle|\downarrow\rangle + |\downarrow\rangle|\uparrow\rangle\Big] \\ |1,-1\rangle &= |\downarrow\rangle|\downarrow\rangle \end{aligned}\right\}\quad s=1 \text{ üçlü durum (triplet)}$$

s=1, m=0 durumuna ortogonal durum;

$$|0, 0\rangle = \frac{1}{\sqrt{2}}\Big[|\uparrow\rangle|\downarrow\rangle - |\downarrow\rangle|\uparrow\rangle\Big] \quad s=0 \text{ (tekli durum) (singlet)}$$

Kontrol için;

- $$S_-|1,0\rangle = S_-\Big[\frac{1}{\sqrt{2}}|\uparrow\rangle|\downarrow\rangle + \frac{1}{\sqrt{2}}|\downarrow\rangle|\uparrow\rangle\Big]$$

$$= \Big[\frac{1}{\sqrt{2}}\big(\underbrace{S_-^{(1)}|\uparrow\rangle}_{\hbar|\downarrow\rangle}\big)|\downarrow\rangle + \frac{1}{\sqrt{2}}|\uparrow\rangle\big(\underbrace{\cancel{S_-^{(2)}|\downarrow\rangle}}_{0}\big)\Big]$$

$$+ \Big[\frac{1}{\sqrt{2}}\big(\underbrace{\cancel{S_-^{(1)}|\downarrow\rangle}}_{0}\big)|\uparrow\rangle + \frac{1}{\sqrt{2}}|\downarrow\rangle\big(\underbrace{S_-^{(2)}|\uparrow\rangle}_{\hbar|\downarrow\rangle}\big)\Big]$$

$$S_-|1,0\rangle = \frac{\hbar}{\sqrt{2}}|\downarrow\rangle|\downarrow\rangle + \frac{\hbar}{\sqrt{2}}|\downarrow\rangle|\downarrow\rangle$$

$$= \frac{2\hbar}{\sqrt{2}}|\downarrow\rangle|\downarrow\rangle$$

$$S_-|1,0\rangle = \hbar\sqrt{2}\,|1,-1\rangle, \quad S_+|1,0\rangle \longrightarrow |1,1\rangle$$

- $$S_-|0,0\rangle = \left(S_-^{(1)} + S_-^{(2)}\right)\left[\frac{1}{\sqrt{2}}|\uparrow\rangle|\downarrow\rangle - \frac{1}{\sqrt{2}}|\downarrow\rangle|\uparrow\rangle\right]$$

$$= \frac{1}{\sqrt{2}}\left(\underbrace{S_-^{(1)}|\uparrow\rangle}_{\hbar|\downarrow\rangle}\right)|\downarrow\rangle + \frac{1}{\sqrt{2}}|\uparrow\rangle\left(\cancel{S_-^{(2)}|\downarrow\rangle}\right) - \frac{1}{\sqrt{2}}\left(\cancel{S_-^{(1)}|\downarrow\rangle}\right)|\uparrow\rangle - \frac{1}{\sqrt{2}}|\downarrow\rangle\left(\underbrace{S_-^{(2)}|\uparrow\rangle}_{\hbar|\downarrow\rangle}\right)$$

$$= \frac{\hbar}{\sqrt{2}}|\downarrow\rangle|\downarrow\rangle - \frac{\hbar}{\sqrt{2}}|\downarrow\rangle|\downarrow\rangle$$

$$S_-|0,0\rangle = 0$$

$$S_+|0,0\rangle = 0$$

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5.2. Spini 1 ve spini 2 olan iki parçacık toplam spini 3 ve z bileşeni ħ olan bir düzenekte durağan durumdadır. Spini 2 olan parçacığın z bileşenini ölçtüğümüzde hangi değerler hangi olasılıklar ile elde edilir?

$$\left.\begin{array}{l} S^{(1)} = 1, \\ S^{(2)} = 2, \end{array}\right\} \quad S^{Top} = \boxed{3}, 2, 1$$

sistem $S = 3$ ve $m_S = 1$ durumunda; $|S, m_S\rangle = \underline{|3,1\rangle}$

$$|3,1\rangle = a\,|1, m_{S1}\rangle|2\, m_{S2}\rangle + b\,|1, m_{S1}\rangle|2\, m_{S2}\rangle \cdots$$

$m_{S1} + m_{S2} = 1$ olmalı;

$$\left.\begin{array}{l} m_{S1} = -1, 0, 1 \\ m_{S2} = -2, -1, 0, 1, 2 \end{array}\right\} \text{olabilirler.}$$

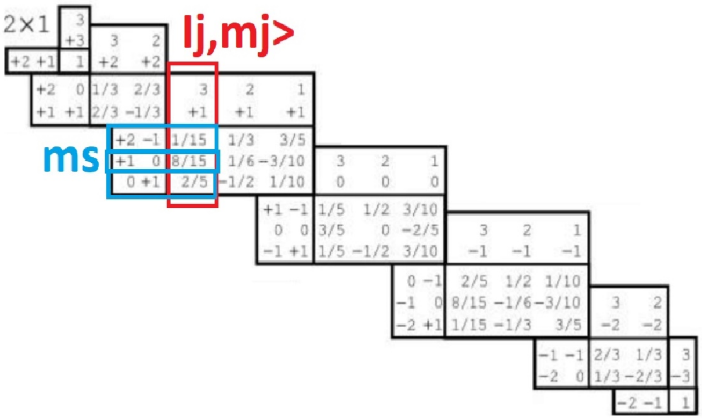
$m_{S1} = 1, \quad m_{S2} = 1 \longrightarrow m_S = 2$ ✗

$m_{S1} = 1, \quad m_{S2} = 0 \longrightarrow m_S = 1$ ✓

$m_{S1} = 1, \quad m_{S2} = -1 \longrightarrow m_S = 0$ ✗

$m_{S1} = -1, \quad m_{S2} = 2 \longrightarrow m_S = 1$ ✓

$m_{S1} = 0, \quad m_{S2} = 1 \longrightarrow m_S = 1$ ✓



$$a = \sqrt{\frac{6}{15}}, \quad b = \sqrt{\frac{1}{15}}, \quad c = \sqrt{\frac{8}{15}}$$

$$|3,1\rangle = a\,|1,1\rangle|2,0\rangle + b\,|1,-1\rangle|2,2\rangle + c\,|1,0\rangle|2,1\rangle$$

$$a = \sqrt{\frac{6}{15}}, \quad b = \sqrt{\frac{1}{15}}, \quad c = \sqrt{\frac{8}{15}}$$

$$|3,1\rangle = \sqrt{\frac{6}{15}}\,|1,1\rangle|2,0\rangle + \sqrt{\frac{1}{15}}\,|1,-1\rangle|2,2\rangle + \sqrt{\frac{8}{15}}\,|1,0\rangle|2,1\rangle$$

$$S_z^{(2)}|3,1\rangle = \sqrt{\frac{6}{15}}\,|1,1\rangle \underbrace{S_z^{(2)}|2,0\rangle}_{0\hbar|2,0\rangle} + \frac{1}{\sqrt{15}}\,|1,-1\rangle \underbrace{S_z^{(2)}|2,2\rangle}_{2\hbar|2,2\rangle} + \sqrt{\frac{8}{15}}\,|1,0\rangle \underbrace{S_z^{(2)}|2,1\rangle}_{\hbar|2,1\rangle}$$

$$P(S_z = 0\hbar) = |\langle 2,0|3,1\rangle|^2 = \frac{6}{15}, \qquad P(S_z = \hbar) = |\langle 2,1|3,1\rangle|^2 = \frac{8}{15},$$

$$P(S_z = 2\hbar) = |\langle 2,2|3,1\rangle|^2 = \frac{1}{15},$$

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5.3. Spini aşağı olan bir elektron Hidrojen atomunun ψ_{510} durumundadır. Yalnızca elektronun (protonun spini hariç) toplam açısal momentumunun karesi ölçüldüğünde hangi değerler hangi olasılıklar ile elde edilir?

$e^- \longrightarrow s = 1/2$

spin aşağı $\longrightarrow m_s = -1/2$

$\psi_{510} \longrightarrow n=5,\; l=1,\; m_l=0$

$|l-s| \leq j \leq l+s$

$|l-s| \leq j \leq l+s$

$|1-1/2| \leq j \leq 1+1/2$

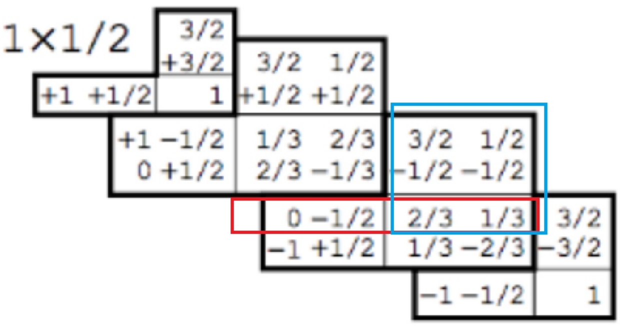
$j : 3/2,\ 1/2$

$m_j = m_l + m_s = 0 - 1/2 = -1/2$

$$\psi_{tüm} = \psi_{510}\, \psi_{\underset{aşağı}{spin}} = |\psi_{510}\rangle |\tfrac{1}{2}, -\tfrac{1}{2}\rangle$$

$$|\overset{l}{1}, \overset{m_l}{0}\rangle |\overset{s}{\tfrac{1}{2}}, \overset{m_s}{-\tfrac{1}{2}}\rangle = a\, |\overset{j}{\tfrac{3}{2}}\ \overset{m_j}{-\tfrac{1}{2}}\rangle + b\, |\overset{j}{\tfrac{1}{2}}, \overset{m_j}{-\tfrac{1}{2}}\rangle$$

$$|1,0\rangle |\tfrac{1}{2}, -\tfrac{1}{2}\rangle = \sqrt{\tfrac{2}{3}}\, |\tfrac{3}{2}, -\tfrac{1}{2}\rangle + \sqrt{\tfrac{1}{3}}\, |\tfrac{1}{2}, -\tfrac{1}{2}\rangle$$



Clebsch-Gordan katsayılarından;

$a = \sqrt{\tfrac{2}{3}}\ ,\quad b = \sqrt{\tfrac{1}{3}}$

$$J^2 |j, m_j\rangle = \hbar^2 j(j+1) |j, m_j\rangle$$

$$J^2 |1,0\rangle |1/2, -1/2\rangle = \sqrt{\tfrac{2}{3}}\, \underbrace{J^2 |3/2, -1/2\rangle}_{\hbar^2 \frac{15}{4} |3/2, -1/2\rangle} + \sqrt{\tfrac{1}{3}}\, \underbrace{J^2 |1/2, -1/2\rangle}_{\hbar^2 \frac{3}{4} |1/2, -1/2\rangle}$$

$J^2 : \dfrac{15\hbar^2}{4}$ $\qquad$ $J^2 : \dfrac{3\hbar^2}{4}$

$$P\left(J^2 = \tfrac{15\hbar^2}{4}\right) = \left| \langle \tfrac{3}{2}, m_j | \left(|1,0\rangle |1/2, -1/2\rangle \right) \right|^2 = \tfrac{2}{3}$$

$$P\left(J^2 = \tfrac{3\hbar^2}{4}\right) = \left| \langle 1/2, m_j | \left(|1,0\rangle |1/2, -1/2\rangle \right) \right|^2 = 1/3$$

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5.4. Bir Hidrojen atomundaki elektronun toplam (tüm) dalga fonksiyonu,

$$\psi = R_{21}\left(\sqrt{\tfrac{1}{3}}\, Y_1^0 \chi_+ + \sqrt{\tfrac{2}{3}}\, Y_1^1 \chi_-\right)$$

olarak verilmiştir,

a) L^2 ölçülürse hangi değerler hangi olasılıklarla elde edilir?

b) L_z " " " " " " "

c) S^2 " " " " " " "

d) S_z " " " " " " "

e) J^2 " " " " " " "

f) " " " " " " " "

g) Parçacığın konumunu ölçerseniz, (r, θ, ϕ) noktasında bulunma olasılık yoğunluğu nedir?

$$\psi = R_{21}\left(\sqrt{\tfrac{1}{3}}\, \underset{\substack{l=1\\ m_l=0}}{Y_1^0} \chi_+ + \sqrt{\tfrac{2}{3}}\, \underset{\substack{l=1\\ m_l=0}}{Y_1^{+1}} \chi_-\right)$$

R_{21}: $n=2$, $l=1$

$s \quad m_s$

$\chi_\pm = |\tfrac{1}{2}, \pm \tfrac{1}{2}\rangle$

$R_{nl}\, Y_l^m$

$$E_n = -\frac{13{,}6\,eV}{n^2} \longrightarrow E_2 = -\frac{13{,}6\,eV}{4}$$

a : $L^2 |n,l,m\rangle = \hbar^2 l(l+1)|n,l,m\rangle$

$$L^2\psi = L^2\left(R_{21}\sqrt{\tfrac{1}{3}}\, Y_1^0\chi_+ + R_{21}\sqrt{\tfrac{2}{3}}\, Y_1^1\chi_-\right)$$

$$= \hbar^2\, 1(1+1)\,\psi \;-\; L^2 = 2\hbar^2, \ \%100 \text{ olasılıkla},$$

$$P(L^2 = 2\hbar^2) = 1$$

b : $L_z |n,l,m_l\rangle = m_l\hbar\, |n,l,m_l\rangle$

$$L_z\psi = R_{21}\left[\sqrt{\tfrac{1}{3}}\, \underbrace{L_z Y_1^0}_{0\hbar\, Y_1^0}\chi_+ + \sqrt{\tfrac{2}{3}}\, \underbrace{L_z Y_1^1}_{\hbar\, Y_1^1}\chi_-\right]$$

L_z; $0\hbar$, $\hbar$ $\qquad P(L_z = 0\hbar) = \tfrac{1}{3}$, $\quad P(L_z = \hbar) = \tfrac{2}{3}$

c) $S^2|s,m_s\rangle = \hbar^2 s(s+1)|s,m_s\rangle$

$$S^2\chi = R_{21}\left(\sqrt{\tfrac{1}{3}}\,Y_1^0\,\underbrace{S^2\chi_+}_{\hbar^2\frac{1}{2}(\frac{3}{2})} + \sqrt{\tfrac{2}{3}}\,Y_1^1\,\underbrace{S^2\chi_-}_{\hbar^2\frac{1}{2}(\frac{3}{2})}\right) \Rightarrow S^2 = \frac{3\hbar^2}{4} \quad \%100$$

$P(S^2 = 3\hbar^2/4) = 1$

d) $S_z|s,m_s\rangle = m_s\hbar|s,m_s\rangle$

$$S_z\chi = R_{21}\left[\sqrt{\tfrac{1}{3}}\,Y_1^0\,\underbrace{S_z|\tfrac{1}{2},+\tfrac{1}{2}\rangle}_{\frac{\hbar}{2}|1/2,1/2\rangle} + \sqrt{\tfrac{2}{3}}\,Y_1^1\,\underbrace{S_z|1/2,-1/2\rangle}_{-\frac{\hbar}{2}|1/2,-1/2\rangle}\right]$$

$$S_z\chi = \begin{cases} \hbar/2, & P(S_z = \hbar/2) = 1/3 \\ -\hbar/2, & P(S_z = -\hbar/2) = 2/3 \end{cases}$$

e) $l = 1,\ m_l = 0, 1$

$s = 1/2 \quad m_s = -1/2, +1/2$

$$\chi = \sqrt{\tfrac{1}{3}}\,\underbrace{R_{21}Y_1^0\chi_+}_{\substack{l=1,\ s=1/2 \\ m_l=0 \quad m_s=1/2 \\ j=3/2,\ 1/2 \\ m_j=1/2}} + \sqrt{\tfrac{2}{3}}\,\underbrace{R_{21}Y_1^1\chi_-}_{\substack{l=1,\ s=1/2 \\ m_l=1,\ m_s=-1/2 \\ j=3/2,\ 1/2 \\ m_j=1/2}}$$

$a|\underset{j}{3/2},\underset{m_j}{1/2}\rangle + b|\underset{j}{1/2}\ \underset{m_j}{1/2}\rangle \qquad c|1/2\ 1/2\rangle + d|3/2,1/2\rangle$

$a = c = \sqrt{\tfrac{2}{3}}$, $b = d = \sqrt{\tfrac{1}{3}}$ } tabloda

$$\chi = R_{21}\left(\sqrt{\tfrac{1}{3}}\left(\sqrt{\tfrac{2}{3}}|3/2,1/2\rangle + \sqrt{\tfrac{1}{3}}|1/2,1/2\rangle\right) + \sqrt{\tfrac{2}{3}}\left(\sqrt{\tfrac{2}{3}}|1/2,1/2\rangle + \sqrt{1/3}|3/2,1/2\rangle\right)\right)$$

$$\chi = R_{21}\left(\frac{2\sqrt{2}}{3}|\tfrac{3}{2},1/2\rangle + 1/3|1/2,1/2\rangle\right)$$

$j^2 = \frac{\hbar^2 15}{4},\ P = \frac{8}{9}$

$j^2 = \frac{3\hbar^2}{4},\ P = 1/9$

$j_z = \hbar/2 \rightarrow P = \%100$

g)

$$|\chi|^2 = \chi^* \chi$$

$$|\chi|^2 = \underbrace{R_{21}^* \left(\sqrt{\frac{1}{3}}\, Y_1^{0*} \chi_+^* + \sqrt{\frac{2}{3}}\, Y_1^{1*} \chi_-^* \right)}_{\chi^*} \underbrace{R_{21} \left(\sqrt{\frac{1}{3}}\, Y_1^{0} \chi_+^* + \sqrt{\frac{2}{3}}\, Y_1^{1} \chi_- \right)}_{\chi}$$

$$|\chi|^2 = |R_{21}|^2 \left[\frac{1}{3} |Y_1^0|^2 + \frac{2}{3} |Y_1^1|^2 \right] \qquad Y_1^0 Y_1^1 = 0$$

$$\chi_+ \chi_- = 0$$

$$R_{21} = \frac{1}{\sqrt{24}}\, a^{-3/2}\, \frac{r}{a}\, e^{-r/2a}$$

$$Y_1^0 = \sqrt{\frac{3}{4\pi}} \cos\theta, \quad Y_1^1 = \sqrt{\frac{3}{8\pi}} \sin\theta\, e^{i\phi}$$

$$|\chi|^2 = \frac{1}{24} \frac{r^2}{a^5} e^{-r/a} \left[\frac{1}{\cancel{3}} \frac{\cancel{3}}{4\pi} \cos^2\theta + \frac{2}{\cancel{3}} \frac{\cancel{3}}{8\pi} \sin^2\theta \right] = \frac{1}{24} \frac{r^2}{a^5} e^{-r/a} \frac{1}{4\pi}$$

$$|\chi|^2 = \frac{1}{96\pi a^5} r^2 e^{-r/a}$$

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