so: $\psi_{c_1}(\vec{p}) = -\psi_4(-\vec{p})$ $\quad p_0 = E \quad$ couples to $\vec{A}$ with $+e$

Likewise: $\psi_{c_2}(\vec{p}) = \psi_3(-\vec{p})$ $\quad p_0 = E \quad +e$

$\psi_{c_3}(\vec{p}) = \psi_2(-\vec{p})$ $\quad p_0 = -E \quad +e$

$\psi_{c_4}(\vec{p}) = -\psi_1(-\vec{p})$ $\quad p_0 = -E \quad +e$

Now: get rid of $-E$ states altogether... keeping 4 $+E$ states: 2 regular + 2 charge conjugates.

Call:

$u_1(\vec{p})$	electron	$p_0 = E$	"spin" $\frac{1}{2}$
$u_2(\vec{p})$	"	"	$-\frac{1}{2}$
$v_1(\vec{p}) \equiv u_{c_1}(\vec{p})$	positron	"	$+\frac{1}{2}$
$v_2(\vec{p}) \equiv u_{c_2}(\vec{p})$	"	"	$-\frac{1}{2}$

v's satisfy D.E., with opposite p^μ

$$\left.\begin{aligned} (\not{p}-m)u_i(p) &= 0 \\ (\not{p}+m)v_i(p) &= 0 \end{aligned}\right\} \quad i = 1,2 \quad p_0 = +E$$

We have $\quad \bar{u}_i(p)\, u_j(p) = 2m\,\delta_{ij} \qquad u^\dagger_i u_j = 2E\,\delta_{ij}$

$$\bar{v}_i(p)\, v_j(p) = -2m\,\delta_{ij} \qquad v^\dagger_i v_j = 2E\,\delta_{ij}$$

$$\bar{v}\, u = \bar{u}\, v = 0$$

$$u_s(\vec{p}) = \sqrt{E+m} \begin{pmatrix} \chi^s \\ \frac{\vec{\sigma}\cdot\vec{p}}{E+m}\,\chi^s \end{pmatrix} \qquad s = 1,2$$

$$v_s(\vec{p}) = \sqrt{E+m} \begin{pmatrix} \frac{\vec{\sigma}\cdot\vec{p}}{E+m}\,\chi^{-s} \\ \chi^{-s} \end{pmatrix}$$

$$\chi^1 = \begin{pmatrix} 1 \\ 0 \end{pmatrix} = \chi^{-1} \qquad\qquad \chi^2 = \begin{pmatrix} 0 \\ 1 \end{pmatrix} = \chi^{-2}$$

$\uparrow$ spin $= 1/2$ $\qquad \uparrow$ $-1/2$ $\qquad \uparrow$ $-1/2$ $\qquad \uparrow$ $1/2$ $\qquad$ REST FRAME!

So, spin works funny for antiparticles.

Calculate $\quad \langle \hat{\Sigma}_3 \rangle_1 = \dfrac{u_1^\dagger \Sigma_3 u_1}{u^\dagger_1 u_1}$

numerator: $\quad u_1^\dagger \hat{\Sigma}_3 u_1 = \dfrac{N^2}{2} \left(1, 0, \frac{p_3}{E+m}, \frac{p_-}{E+m}\right) \begin{pmatrix} \sigma_3 & 0 \\ 0 & \sigma_3 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ \frac{p_3}{E+m} \\ \frac{p_+}{E+m} \end{pmatrix}$

$$= \frac{N^2}{2}\left[1 + \frac{p_3^2}{(E+m)^2} - \frac{p_- p_+}{(E+m)^2}\right]$$

$$= \frac{N^2}{2}\left[1 + \frac{p_3^2 - p_1^2 - p_2^2}{(E+m)^2}\right]$$

$$= \frac{N^2}{2}\left[E^2 + m^2 + 2Em + p_3^2 - p_1^2 - p_2^2\right]\frac{1}{(E+m)^2}$$

$$= \frac{1}{2}\left[\cancel{p_1^2} + \cancel{p_2^2} + p_3^2 + m^2 + 2Em + p_3^2 - \cancel{p_1^2} - \cancel{p_2^2}\right]\frac{1}{E+m}$$

$$= \frac{1}{E+m}\left[p_3^2 + Em + m^2\right]$$

not helpful – but spin is a rest frame parameter.

R.F. $$u_1^\dagger \hat{\Sigma}_3 u_1 = \frac{1}{m+m}\left[0 + m^2 + m^2\right] = m$$

from $u^\dagger u = 2m$ in R.F.

$$\langle \hat{\Sigma}_3 \rangle_1 = +1/2$$ which is what "spin 1/2" really means.

What about the charge conjugate states?

$$\psi_c = C\gamma^0\psi^*$$

and

$$\bar{\psi}^T = (\psi^\dagger\gamma^0)^T = \gamma^0\psi^*$$

$$\psi_c = C\bar{\psi}^T$$

so, $\hat{\vec{\Sigma}}\psi_c = \hat{\vec{\Sigma}}C\bar{\psi}^T = CC^{-1}\hat{\vec{\Sigma}}C\bar{\psi}^T$

can show $C^{-1}\hat{\vec{\Sigma}}C = -\hat{\vec{\Sigma}}$

so

$$\hat{\vec{\Sigma}}\psi_c = -C\hat{\vec{\Sigma}}\bar{\psi}^T$$

now $\hat{\Sigma}_3$ $\hat{\Sigma}_3\psi_c = -C\hat{\Sigma}_3\bar{\psi}^T = -C\hat{\Sigma}_3(\psi^\dagger\gamma^0)^T$

$$= -C\hat{\Sigma}_3\gamma^0\psi^*$$

in R.F. $\gamma^0\psi^* = \psi^*$

$$\left(\begin{array}{cc|cc} 1 & & & \\ & 1 & & \\ \hline & & -1 & \\ & & & -1 \end{array}\right)\begin{pmatrix}1\\0\\0\\0\end{pmatrix} = \begin{pmatrix}1\\0\\0\\0\end{pmatrix} \quad \text{etc.}$$

so,

$$\hat{\Sigma}_3\psi_c(p=0) = -C\hat{\Sigma}_3\psi^*(p=0)$$

$$= (-C)\left(\pm\tfrac{1}{2}\psi^*(p=0)\right)$$

$$= \mp\tfrac{1}{2}C\psi^*(0) = \mp\tfrac{1}{2}C\underbrace{\gamma^0}_{RF}\psi^*(0)$$

$$\hat{\Sigma}_3\psi_c(0) = \mp\tfrac{1}{2}\psi_c(0)$$

opposite eigenvalues for antiparticle states

$$\langle\hat{\Sigma}_3\rangle_1 = \frac{\psi^\dagger_{c_1}\hat{\Sigma}_3\psi_{c_1}}{\psi^\dagger_{c_1}\psi_{c_1}} = \frac{v_1^\dagger\hat{\Sigma}_3 v_1}{v_1^\dagger v_1} = -\tfrac{1}{2}$$

How about helicity? $\hat{h} \equiv \vec{\sigma}\cdot\hat{\vec{p}}$

$$\mathbb{H} = \begin{pmatrix} \vec{\sigma}\cdot\hat{\vec{p}} & 0 \\ 0 & \vec{\sigma}\cdot\hat{\vec{p}} \end{pmatrix} = \begin{pmatrix} h & 0 \\ 0 & h \end{pmatrix}$$

$$\langle \hat{h} \rangle_{1,2} = \frac{u_s^\dagger \mathbb{H} u_s}{u_s^\dagger u_s} \qquad s = 1,2$$

$$u_s^\dagger \mathbb{H} u_s = N^2 \left(\chi^{s\dagger}, \left(\frac{\vec{\sigma}\cdot\vec{p}}{E+m} \chi^s \right)^\dagger \right) \mathbb{H} \begin{pmatrix} \chi^s \\ \frac{\vec{\sigma}\cdot\vec{p}}{E+m} \chi^s \end{pmatrix}$$

$\vdots$

$$= N^2 \left(\chi^{s\dagger} h \chi^s + \frac{\chi^{s\dagger}\, \vec{\sigma}^\dagger\cdot\vec{p}\ \vec{\sigma}\cdot\hat{p}\ \vec{\sigma}\cdot\vec{p}\, \chi^s}{(E+m)^2} \right)$$

$\vdots$

$$= N^2 \frac{(E^2 + m^2 + 2mE + p^2)}{(E+m)^2} \chi^{\dagger s} h \chi^s$$

$\vdots$

$$= 2E\, \chi^{\dagger s} h \chi^s$$

since $u^\dagger u = 2E$ $\qquad \langle h \rangle_s = \chi^{\dagger s} h \chi^s$

Then for $\quad h = \vec{\sigma}\cdot\hat{p} = \begin{pmatrix} 1 & 1-i \\ 1+i & -1 \end{pmatrix}$

we can work out the particle and antiparticle spinors

$\chi^s = \begin{pmatrix} a \\ b \end{pmatrix}$ in general

$$\chi_s^\dagger h \chi^s = (a^*, b^*) \begin{pmatrix} 1 & 1-i \\ 1+i & -1 \end{pmatrix} \begin{pmatrix} a \\ b \end{pmatrix}$$

$$= a^*a - a^*b - i a^*b + b^*a + i b^*a - b^*b$$

a and b will be chosen to be real

$$= a^2 - b^2 = (a-b)(a+b)$$

for $s=1 \quad a=1 \quad b=0 \qquad \chi^{\dagger s} h \chi^s = 1$

$s=2 \quad a=0 \quad b=1 \qquad \chi^{\dagger s} h \chi^s = -1$

So, u_1 is a state of + helicity

u_2 " − "

Antiparticles go the same way:

$$v_1(p) = \sqrt{E+m} \begin{pmatrix} \frac{\vec{\sigma}\cdot\vec{p}}{E+m} \chi^{-1} \\ \chi^{-1} \end{pmatrix} \quad \text{is + helicity}$$

$v_2(p)$ − helicity

Look at the coupling of $\psi - A$ again

$$(i\not\partial - m)\psi = e\not A\psi$$

substitute $\quad \psi = u e^{-ip\cdot x}$

$$[i\gamma^\mu(-ip_\mu) - m]u e^{-ip\cdot x} = e A^\mu \gamma_\mu u e^{-ip\cdot x}$$

$$[\gamma^0 p_0 - \vec{\gamma}\cdot\vec{p} - m]\psi = e(A^0\gamma_0 - \vec{A}\cdot\vec{\gamma})\psi$$

$$\left[\begin{pmatrix} E & 0 \\ 0 & -E \end{pmatrix} + \begin{pmatrix} 0 & -\vec{\sigma}\cdot\vec{p} \\ \vec{\sigma}\cdot\vec{p} & 0 \end{pmatrix} - \begin{pmatrix} m & 0 \\ 0 & m \end{pmatrix}\right]\psi = \begin{pmatrix} e\phi & -e\vec{\sigma}\cdot\vec{A} \\ e\vec{\sigma}\cdot\vec{A} & -e\phi \end{pmatrix}\psi$$

$$\begin{pmatrix} E - m - e\phi & -\vec{\sigma}\cdot\vec{p} + e\vec{\sigma}\cdot\vec{A} \\ \vec{\sigma}\cdot\vec{p} - e\vec{\sigma}\cdot\vec{A} & -E - m + e\phi \end{pmatrix}\begin{pmatrix} \psi_A \\ \psi_B \end{pmatrix} = 0$$

2 coupled equations again

$$-\vec{\sigma}\cdot(\vec{p} - e\vec{A})\psi_B = (-E + m + e\phi)\psi_A$$

$$\vec{\sigma}\cdot(\vec{p} - e\vec{A})\psi_A = (E + m - e\phi)\psi_B$$

$$\psi_B = \frac{\vec{\sigma}\cdot(\vec{p} - e\vec{A})}{E + m - e\phi}\psi_A$$

substitute

$$-\frac{\vec{\sigma}\cdot(\vec{p} - e\vec{A})\,\vec{\sigma}\cdot(\vec{p} - e\vec{A})}{E + m - e\phi}\psi_A = (-E + m + e\phi)\psi_A$$

make non-relativistic approximation

$\varepsilon \equiv E - m \rightarrow$ small

$e\phi << m$

$$\frac{1}{E+m-e\phi} = \frac{1}{\varepsilon+2m-e\phi} = \frac{1}{2m}\left(\frac{1}{1+\frac{\varepsilon-e\phi}{2m}}\right)$$

$$= \frac{1}{2m}\left(1-\frac{\varepsilon-e\phi}{2m}+\cdots\right)$$

notice $\quad \frac{\varepsilon-e\phi}{2mc^2} \sim \frac{\frac{1}{2}mv^2}{2mc^2} \sim v^2/c^2 \sim \beta^2$

so just keep 1st term

$$\frac{1}{2m}\left[\vec{\sigma}\cdot(\vec{p}-e\vec{A})\,\vec{\sigma}\cdot(\vec{p}-e\vec{A})\right]\psi_A = (\varepsilon-e\phi)\psi_A$$

use σ identity

$$\frac{1}{2m}\left[(\vec{p}-e\vec{A})^2 + i\vec{\sigma}\cdot(\vec{p}-e\vec{A})\times(\vec{p}-e\vec{A})\right]\psi_A =$$

$$\frac{1}{2m}\left[(\vec{p}-e\vec{A})^2 + i\vec{\sigma}\cdot(-\vec{p}\times\vec{A}-\vec{A}\times\vec{p})e\right]\psi_A$$

another operator identity $\quad \vec{p}\times\vec{A} = -i(\vec{\nabla}\times\vec{A}) - \vec{A}\times\vec{p}$

$$\frac{1}{2m}\left[(\vec{p}-e\vec{A})^2 - ei\vec{\sigma}\cdot(i\vec{\nabla}\times\vec{A}) + \vec{A}\times\vec{p} - \vec{A}\times\vec{p}\right]\psi_A$$

$$\frac{1}{2m}\left[\ \underline{\underline{(\vec{p}-e\vec{A})^2}} - e\,\vec{\sigma}\cdot\vec{B} + \underline{\underline{e\phi}}\ \right]\psi_A = \underline{\underline{\varepsilon}}\,\psi_A$$

$=$ The result of spinless Schrödinger wavefunction with the electromagnetic field

$\sim\sim$ This term was added by Pauli in 1927 BY HAND to account for the Anomalous Zeeman Effect.

for $\varepsilon \to 0$ without $\vec{A}$ or ϕ

$$\psi_B \sim \frac{\vec{\sigma}\cdot\vec{p}}{2m}\,\psi_A$$

$$\psi_A \sim -\frac{\vec{\sigma}\cdot\vec{p}}{-E+m}\,\psi_B$$

$$\sim -\frac{\vec{\sigma}\cdot\vec{p}}{-(\varepsilon+m)}\,\psi_B$$

$$\psi_A = \frac{\vec{\sigma}\cdot\vec{p}}{\varepsilon}\,\psi_B$$

for ε small $\quad \psi_A >> \psi_B$

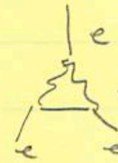
called "upper" or "large" components

and then $\quad \frac{p^2}{2m}\psi_A = \varepsilon\psi_A \quad$ ✓

Remember $\quad \vec{\mu} = -\dfrac{\overset{\swarrow\ \text{gyromagnetic ratio}}{g}\, e}{2m} \vec{J}\, \hbar$

For $\quad \vec{J} = \vec{\sigma}/_2 \quad$ and $\quad g = 2$ for spin $1/2$

$$\vec{\mu} = -\frac{ge}{2m}\frac{\vec{\sigma}}{2}\hbar = \underbrace{-\frac{e\hbar}{2m}}_{-\mu_B^e}\vec{\sigma}$$

The quantity of interest is historically $\dfrac{g-2}{2}$  $+ \cdots$

$$\frac{g_e-2}{2} = 1159.6521811 \pm 0.0000007 \times 10^{-6}$$
$$1159.6521818 \quad \text{theory.}$$

$$\frac{g_\mu - 2}{2} = 11659208 \pm 6 \times 10^{-10}$$

$\Big\} \sim 3\sigma$

$$\left(\frac{g_\mu - 2}{2}\right)_{SM} = 11659181(8) \times 10^{-10}$$

Completeness:

For discrete bases--

$$\psi(x) = \sum_n |n\rangle a^n \qquad \langle n|m\rangle = \delta_{nm}$$

so $\quad a^n = \langle n|\psi\rangle$

$$|\psi\rangle = \underbrace{\sum_n |n\rangle\langle n|}_{= 1} \psi\rangle$$

$1 \equiv$ completeness

For continuous bases:

Remember in QM we can expand an arbitrary solution to S.E. in plane waves as a basis -

$$\psi(\bar{r}) = \int \phi_{\bar{p}}(\vec{r})\, c(\vec{p})\, d^3\vec{p}$$

$$= \int \frac{e^{i\bar{p}\cdot\bar{r}}}{(2\pi)^{3/2}}\, c(\bar{p})\, d^3\bar{p}$$

with normalization $\int \phi^*_{p'}(r)\, \phi_p(r)\, d^3r = \frac{1}{(2\pi)^3} \int e^{i(\bar{p}-\bar{p}')\cdot\bar{r}}\, d^3r$

$$= \delta(\vec{p}-\bar{p}')$$

$\phi^*_{p'}(\bar{r}) \rightarrow \quad \int d^3r$

$$\int d^3r\, \phi^*_{p'}(r)\, \psi(\bar{r}) = \int d^3\bar{r} \int d^3\bar{p}\; \phi^*_{\bar{p}'}(\bar{r})\, \phi_{\bar{p}}(\bar{r})\, c(\bar{p})$$

$$= \int d^3p\; \delta(\bar{p}-\bar{p}')\, c(\bar{p}) = c(\bar{p}')$$

or $$c(\bar{p}) = \int d^3\bar{r}\, \frac{e^{-i\bar{p}\cdot\bar{r}}}{(2\pi)^{3/2}}\, \psi(\bar{r})$$

Substitute back

$$\psi(\bar{r}) = \int d^3\bar{p}\, d^3\bar{r}'\, \phi_{\bar{p}}(\bar{r})\, \phi^*_{\bar{p}}(\bar{r}')\, \psi(\bar{r}')$$

$$= \int d^3r'\, \psi(\bar{r}') \int d^3\bar{p}\; \phi_p(\bar{r})\, \phi^*_p(\bar{r}')$$

$$= \int d^3\bar{r}'\, \delta(\bar{r}-\bar{r}')\, \psi(\bar{r}') = \psi(\bar{r})$$

For solutions to the D.E. :

distinguishes 2 +E & 2 −E solutions

$$\psi_i(r) = \sum_j \int \phi_p^{(j)}(r)_i \, c^{(j)}(p)\, d^3p$$

$i = 1, 2, 3, 4$
Dirac matrices

where $\phi_p^{(j)}(r)_i = \frac{e^{i\bar{p}\cdot\bar{r}}}{(2\pi)^{3/2}} u^{(j)}(\bar{p})_i$

$$= \sum_j \int u^{(j)}(\bar{p}) \frac{e^{i\bar{p}\cdot\bar{r}}}{(2\pi)^{3/2}} c^{(j)}(\bar{p})\, d^3\bar{p}$$

then

$$\sum_{i=1}^{4} \int \phi_{p'}^{(j')}(r)_i^{+} \phi_p^{(j)}(r)_i \, d^3r = \sum_{i=1}^{4} \int d^3r \, u^{(j')+}(\bar{p})_i \, u^{(j)}(p)_i \frac{e^{i(\bar{p}-\bar{p}')\cdot\bar{r}}}{(2\pi)^3}$$

$$= \sum_{i=1}^{4} u^{(j')+}(\bar{p}')_i \, u^{(j)}(\bar{p})_i \, \delta(\bar{p}-\bar{p}')$$

$$= 2p^0 \delta_{j'j} \, \delta(\bar{p}-\bar{p}') \qquad \text{from our normalization}$$

Do same thing $\sum_m \phi^{(j')+}(r)_m \rightarrow \int d^3r$

$$\sum_m \int d^3r \, \phi_{p'}^{(j')}(r)_m^{+} \psi_m(r) = \sum_m \sum_j \int d^3r \, d^3p \, \phi_{\bar{p}'}^{(j')}(r)_m^{+} \phi_{\bar{p}}^{(j)}(\bar{r})_m \, c^{(j)}(\bar{p})$$

$$= \sum_j \int d^3p \, 2p^0 \delta_{jj'} \, \delta(\bar{p}-\bar{p}') \, c^{(j)}(\bar{p})$$

$$= \sum_j 2p^0 \delta_{jj'} \, c^{(j)}(\bar{p}')$$

So, $c^{(j)}(p) = \frac{1}{2p^0} \sum_m \int d^3r' \, \phi_p^{(j')}(r')^{+}_m \psi_m(\bar{r}')$

Substitute

$$\psi_i(\bar{r}) = \sum_j \sum_m \int d^3p \int d^3r' \, \frac{1}{2p_0} \, \phi_p^{(j)}(\bar{r})_i \, \phi_p^{(j)}(\bar{r}')^{+}_m \psi_m(\bar{r}')$$

$$= \sum_j \sum_m \int \frac{d^3p}{(2\pi)^3} \int d^3r' \, \frac{1}{2p^0} \, u^{(j)}(p)_i \, u^{(j)+}(p)_m \, e^{i(r-r')\cdot\bar{p}} \, \psi_m(r')$$

need it to be "complete" so,

$$\sum_j u^{(j)}(p)_i \, u^{(j)}(p)^{+}_m = 2p_0 \, \delta_{im}$$

for all 4 solutions

4×4 matrix

sort of like, but different from orthonormality

$$\sum_i u^{(j')}(p)^{+}_i \, u^{(j)}(p)_i = \delta_{j'j} \, 2p_0$$

which is a <u>number</u>.

Now, we have the u and v solutions, so only $+E$ spinors

So this becomes

$$\sum_{i=1}^{2} u^{(j)}(p)_i \, \bar{u}^{(j)}(p)_m - \sum_{j=1}^{2} v^{(j)}(p)_i \, \bar{v}^{(j)}(p)_m = \delta_{im} 2m$$

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These are related to projection operators.

Suppose we have a general ψ – and want operators which project out the particle and antiparticle solutions. Conventionally:

$$\Lambda^+ \psi \to u \qquad \& \qquad \Lambda^- \psi \to v$$

"Projection operators for energy and momentum"

easy to construct them $\qquad (\not{p} - m) u(p) = 0$
$\qquad\qquad\qquad\qquad\qquad (\not{p} + m) v(p) = 0$

so,

$$\Lambda^+(p) \equiv \frac{(\not{p} + m)}{2m} \qquad \Lambda^-(p) = \frac{(-\not{p} + m)}{2m}$$

such that

$$\Lambda^+(p) u(p) = \frac{(\not{p} + m)}{2m} u = \frac{\not{p} u + m u}{2m} = \frac{m u + m u}{2m} = u$$

$$\Lambda^+(p) v(p) = \frac{(\not{p} + m)}{2m} v = \frac{\not{p} v + m v}{2m} = \frac{-m v + m v}{2m} = 0$$

ditto

$$\Lambda^-(p) v(p) = v(p) \quad \& \quad \Lambda^-(p) u(p) = 0$$

Sometimes you see single set

$$w^{(j)}(p) \qquad j = 1,2 \quad \text{particles}$$
$$= 3,4 \quad \text{antiparticles}$$

$$\sum_{j=1}^{4} \bar{w}^{(j)}(p)_i\, w^{(h)}(p)_i = \eta^{(j)} \delta_{jh}\, 2m \qquad \eta^{(j)} = 1 \quad j = 1,2$$
$$= -1 \quad 3,4$$

BACK

and
$$\left.\begin{array}{c}\Lambda^+\Lambda^- = \Lambda^-\Lambda^+ = 0\\ \Lambda^+\Lambda^+ = \Lambda^+\\ \Lambda^-\Lambda^- = \Lambda^-\\ \Lambda^+ + \Lambda^- = 1\end{array}\right\}$$ standard requirements for P.O.'s

Now, note:

$$\sum_{i=1}^{2} u^{(i)}\bar{u}^{(i)} = \sum_{i=1}^{2}\eta^{(i)}u^{(i)}\bar{u}^{(i)}$$

$$= \Lambda^+ \sum_{i=1}^{4}\eta^{(i)} w^{(i)}\bar{w}^{(i)}$$

$$= \frac{(\not{p}+m)}{2m}\, 2m = (\not{p}+m)$$

so,
$$\sum_{i=1}^{2} u^{(i)}_n(p)\,\bar{u}^{(i)}_m(p) = 2m\,\Lambda^+(p)_{nm} = (\not{p}+m)_{nm}$$

and
$$\sum_{i=1}^{2} v^{(i)}_n(p)\,\bar{v}^{(i)}_m(p) = -\sum_{i=1}^{2}\eta^{(i)} v^{(i)}_n(p)\,\bar{v}^{(i)}_m(p)$$

$\eta^{(i)} = -1$
$i=1,2$ for antiparticles

$$= -\Lambda^-_{nm}(p)\underbrace{\sum_{i=1}^{4}\eta^{(i)} w^{(i)}_n(p)\,\bar{w}^{(i)}_m(p)}_{2m}$$

$$= -2m\,\Lambda^-_{nm}(p)$$

$$= (\not{p}-m)_{nm}$$