Scotogenic $U(1)_\chi$ Dirac Neutrinos

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Why Dirac Neutrinos ?

In the $SU(3)_C \times SU(2)_L \times U(1)_Y$ standard model (SM), the neutrino ν only appears as part of an $SU(2)_L \times U(1)_Y$ doublet $(\nu, e)_L$. As such, it is massless but neutrino oscillations require that at least two neutrinos are massive. The most accepted way to do this is to add ν_R as a singlet (which is trivial under the SM gauge group), so that $\nu_{L,R}$ are linked by a Dirac mass m_D, but ν_R is also allowed a Majorana mass M. If M is large, we get the famous seesaw mechanism, i.e. $m_\nu \simeq m_D^2/M$, and neutrinos are predicted to be

Majorana! (End of Story)

For years, neutrinoless double beta decay experiments have been the best hope of verifying this theoretical assertion, but to no avail. It is time to reappraise the base assumptions which led to our strong belief that neutrinos are Majorana.

First and foremost is our trust in the SM gauge group, but if that is strictly true, then ν_R has no place in the SM because it is a trivial singlet. Now comes the potent argument based on

$SO(10) \to SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ in which case ν_R must exist as part of an $SU(2)_R \times U(1)_{B-L}$ doublet. Furthermore, the breaking of gauge $B-L$ by a scalar triplet $(\Delta^{++}, \Delta^{+}, \Delta^{0})$ under $SU(2)_R \times U(1)_{B-L}$ implies also a Majorana mass for ν_R from $\langle \Delta^0 \rangle$ which carries two units of $B-L$ charge. We are back to the seesaw mechanism! (End of Story Again)

In 2013, a different story appeared. A simple truth was pointed out (Ma/Picek/Radovcic) that if gauge $U(1)_X$ is broken by a singlet scalar with 3 units of X charge, then it is impossible for a neutral singlet fermion carrying 1 unit of X charge to acquire a Majorana mass. In 2014, this idea was applied to Dirac neutrinos (Ma/Srivastava). The lesson we learned is that the residual symmetry of broken gauge $B-L$ does not have to be Z_2 resulting in Majorana neutrinos. It could be global U(1), or Z_N. This observation led to the renewed interest in Dirac neutrinos and there have been a number of studies in recent years.

In 2013, the first Z_4 model (Heeck/Rodejohann) predicts quadruple beta decay. In 2015, the first Z_3 model (Ma/Pollard/Srivastava/Zakeri) predicts long-lived dark matter which decays to 2 neutrinos.

Why $U(1)_\chi$?

To accommodate ν_R, keep $SO(10)$ but instead of the left-right decomposition, take $SU(5) \times U(1)_\chi$. Now the fermions belong to $\underline{16} = (5^*, 3) + (10, -1) + (1, -5)$, and the scalars belong to $\underline{10} = (5^*, -2) + (5, 2)$.

Under $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_\chi$,

$(5^*, 3) = d^c[3^*, 1, 1/3, 3] + (\nu, e)[1, 2, -1/2, 3]$,

$(10, -1) = u^c[3^*, 1, -2/3, -1] + (u, d)[3, 2, 1/6, -1] + e^c[1, 1, 1, -1]$, $\quad (1, -5) = \nu^c[1, 1, 0, -5]$,

$\Phi_1 = (\phi_1^0, \phi_1^-)[1, 2, -1/2, -2]$,

$\Phi_2 = (\phi_2^+, \phi_2^0)[1, 2, 1/2, 2]$.

In previous theoretical studies, $U(1)_\chi$ is mostly ignored, although the Z_χ gauge boson is still routinely searched for, with $m_{Z_\chi} > 4.1$ TeV based on present LHC data. Since ν^c has $Q_\chi = -5$, it couples to ν through the allowed interaction $\nu^c(\nu\phi_2^0 - e\phi_2^+)$. Thus (ν, ν^c) form a Dirac neutrino pair. However, the breaking of $U(1)_\chi$ by the scalar singlet $\zeta \sim (1, -10)$ from the $\underline{126}$ of $SO(10)$ would also make ν^c massive. Hence the seesaw mechanism occurs as in the left-right case, only the context is changed. Since ζ and $\Phi_{1,2}$ all have even Q_χ, $U(1)_\chi$ breaks to $(-1)^{Q_\chi}$ just as L breaks to $(-1)^L$.

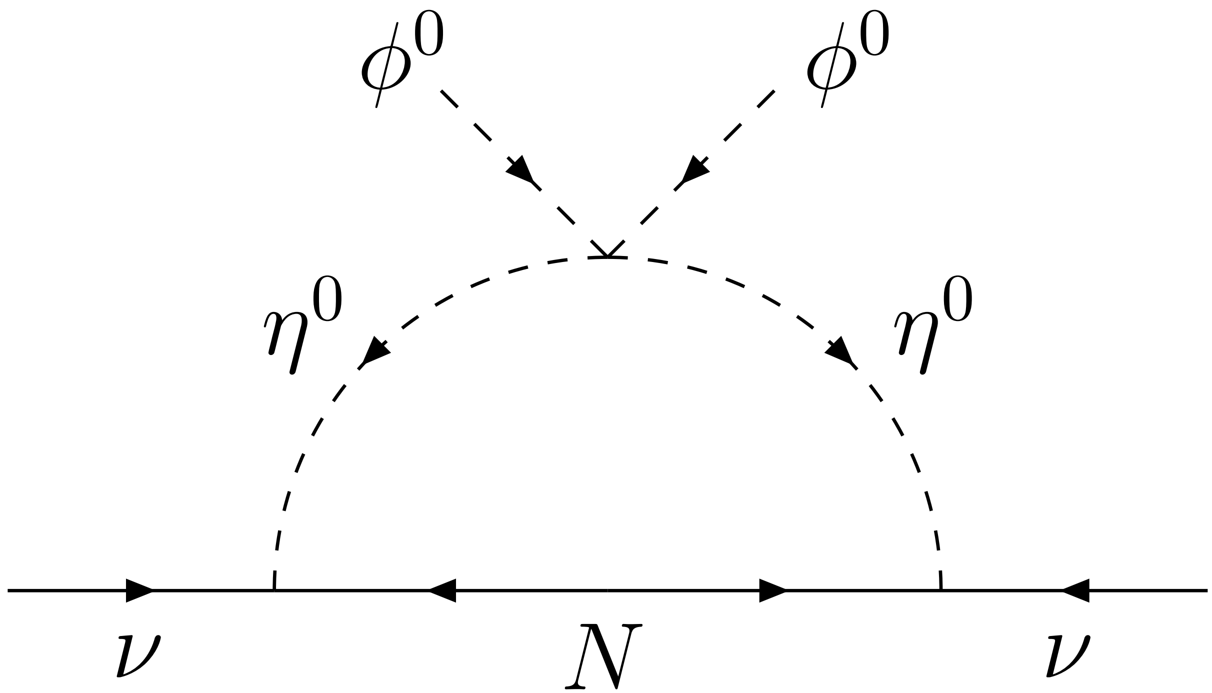
All SM fermions + ν_R have odd Q_χ, whereas the scalars $\Phi_{1,2}$ which couple to them have even Q_χ. The residual discrete symmetry $R_\chi = (-1)^{Q_\chi + 2j}$ is thus even for all of the SM particles, including the gauge bosons because they have $Q_\chi = 0$ and $j = 1$. It is now an easy step to realize that any fermion/scalar with even/odd $U(1)_\chi$ has odd R_χ and belongs to the dark sector. Previously, motivated by supersymmetry, $(-1)^{3(B-L)+2j}$ has been used as dark parity, which is equivalent to R_χ because $15(B-L) = 12Y - 3Q_\chi$. Note that $W_R^\pm$ is absent here and $U(1)_\chi$ is orthogonal to $U(1)_Y$.

To insist on Dirac neutrinos, ζ should not be $(1,-10)$ from the $\underline{126}$, but rather $(1,15)$ from the $\underline{672}$. In that case, global B and L remain unbroken. However, the allowed Yukawa Dirac coupling must then be very small for neutrino masses. To overcome this possible objection, a seesaw scenario may be implemented with the help of $U(1)_\chi$ and a softly broken Z_2 discrete symmetry as shown recently [Ma, arXiv:1811.09645].

In this talk, a further suppression is achieved using dark matter so that Dirac neutrinos masses are obtained radiatively.

Why Scotogenic ?

The original idea that neutrino mass is generated in one loop [Ma, PRD 73, 077301 (2006)] through dark matter (scoto is Greek for darkness) assumes a Z_2 parity which is even for ordinary matter and odd for dark matter. This dark parity is subsequently shown [Ma, PRL 115, 011801 (2015)] to be derivable from lepton parity, and more recently [Ma, PRD 98, 091701(R) (2018)] from Q_χ. This means that a natural link exists between radiative neutrino mass and dark matter. The former exists because neutrinos interact with the latter.


ϕ^0
ϕ^0
η^0
η^0
ν
N
ν

Majorana neutrino masses may be naturally scotogenic because they come from a dimension-five operator. In the absence of mediating particles (singlet neutral fermion, complex triplet scalar, Majorana triplet fermion) at tree level, i.e. the Types I,II,III seesaw, so named in [Ma, PRL 81, 1171 (1998)], particles in the dark sector may be postulated to appear in a loop which generates the neutrino mass.

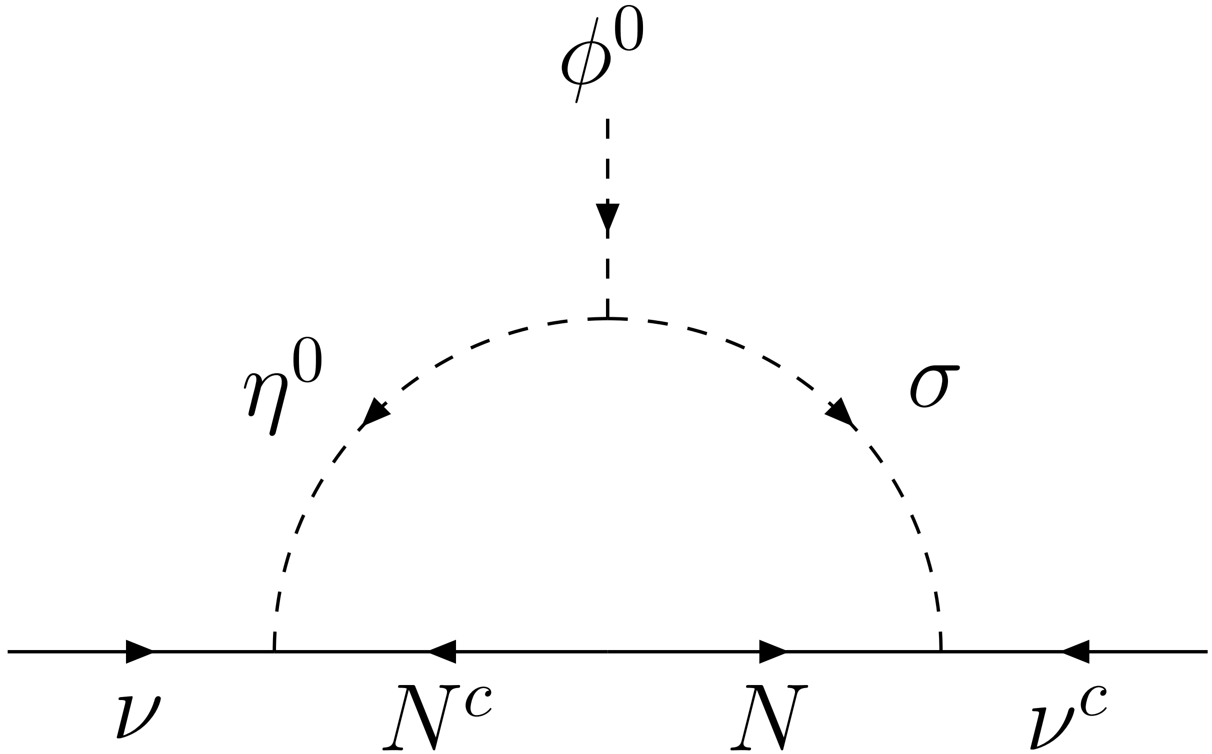
With the insight that these particles are scalars with odd Q_χ and fermions with even Q_χ, no new imposed dark parity is needed.

With Dirac neutrinos, since the dimension-four term $\nu\nu^c\phi^0$ is usually allowed (for $B-L=1$ for ν^c), it must be forbidden by a symmetry which is then softly broken to enable a Dirac mass to appear in one loop. First examples are Gu/Sarkar, PRD 77, 105031 (2008) and Farzan/Ma, PRD 86, 033007 (2012). [Instead of $B-L=1,1,1$ for ν^c, the anomaly-free set $B-L=4,4,-5$ may be chosen [Montero/Pleitez, PLB 675, 64 (2009); Ma/Srivastava, PLB 741, 217 (2015)]. Recent studies include Bonilla/Centelles Chulia/ Cepedello/Peinada/Srivastava, arXiv:1812.01599, and Calle/Restrepo/Yaguna/Zapata, arXiv:1812.05523.]

Model with $U(1)_L$ and Dark Z_3 or $U(1)$

In the $U(1)_\chi$ context, the interactions of fermion and scalar multiplets are restricted. Hence residual conserved global B and L symmetries are possible after the spontaneous breaking of gauge $U(1)_\chi$ by $\zeta \sim 15$. It is now impossible for $\nu^c \sim -5$ to obtain a Majorana mass. Hence neutrinos are Dirac at tree level unless forbidden by an extra symmetry. The simplest is an Z_2 parity under which ν^c is odd. However, this parity must be softly (or spontaneously) broken to allow Dirac neutrinos masses to appear in one or more loops.

particle	$SO(10)$	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_\chi$	Z_2^A	Z_2^B
(u,d)	16	3	2	1/6	-1	$+$	$+$
u^c	16	3^*	1	$-2/3$	-1	$+$	$+$
d^c	16	3^*	1	1/3	3	$+$	$+$
(ν,e)	16	1	2	$-1/2$	3	$+$	$+$
ν^c	16	1	1	0	-5	$-$	$-$
e^c	16	1	1	1	-1	$+$	$+$
N	126^*	1	1	0	10	$-$	$+$
N^c	126	1	1	0	-10	$+$	$+$
(ϕ^+,ϕ^0)	10	1	2	1/2	2	$+$	$+$
(η^+,η^0)	144	1	2	1/2	7	$+$	$+$
σ	16	1	1	0	-5	$+$	$-$
ζ	672	1	1	0	15	$+$	$+$


ϕ^0
η^0
σ
ν
N^c
N
ν^c

The dimension-four terms must respect Z_2, so ν does not couple to ν^c through ϕ^0. However, ν may couple to N^c through η^0 and ν^c to N through σ. In Z_2^A, the $\bar{\phi}^0 \eta \sigma$ term is even, but the $N N^c$ term is odd, hence Z_2^A is broken softly to complete the loop. In Z_2^B, it is the other way round. They both forbid the $\zeta \nu^c N^c$ term, thereby allowing the conservation of L. In either case, $L = 1$ for ν, N and $L = -1$ for ν^c, N^c.

They are however distinguished by the term $\zeta \sigma^3$ which is allowed in Z_2^A and forbidden in Z_2^B.

In Z_2^A, the would-be dark U(1) symmetry is broken to Z_3, with ω for σ, N^c and ω^2 for η, N, where $\omega = \exp(2\pi i/3)$. In Z_2^B, the dark U(1) symmetry has $D = 1$ for σ, N^c and $D = -1$ for η, N.

Instead of using a discrete or global symmetry to forbid the tree-level Dirac coupling, a gauge symmetry may be considered, in which case the only option is spontaneous breaking, and the operator which generates the Dirac neutrino mass is dimension-five. Another option to forbid the tree-level coupling is to use a non-Abelian discrete family symmetry, such as $\Delta(27)$ [Ma, in preparation].

To compute the one-loop Dirac neutrino mass, let the scalar mass eigenstates be

$\chi_1 = \cos\theta\sigma - \sin\theta\bar{\eta}^0, \quad \chi_2 = \sin\theta\sigma + \cos\theta\bar{\eta}^0,$

where θ is the mixing angle due to the $\bar{\phi}^0\eta^0\sigma$ term. Then the 3×3 neutrino mass matrix is given by

$$\sum_k \frac{h^L_{ik}h^R_{jk}\sin 2\theta M_k}{16\pi^2}[F(m_2^2, M_k^2) - F(m_1^2, M_k^2)],$$

where $F(x,y) = [x/(x-y)]\ln(x,y)$. This is the familiar radiative seesaw if $|m_2^2 - m_1^2| << m_2^2 + m_1^2 << M_k^2$.

If $M_k << m_{1,2}$, then [Ma, PLB 717, 235 (2012)]
$(\mathcal{M}_\nu)_{ij} = (\sin 2\theta/16\pi^2) \ln(m_2^2/m_1^2) \sum_k h^L_{ik} h^R_{jk} M_k$,
which is not a seesaw at all! It allows N to be light dark matter, say $m_N = 6$ GeV.

Since N interacts with nuclei through Z_χ, the latest XENON result puts a bound of about 4.5 TeV on its mass, using $\alpha_\chi = g^2_{Z_\chi}/4\pi = 0.0154$.

The correct relic density from $N\bar{N} \to \nu\bar{\nu}$ through χ_1 exchange is obtained with $m_1 = 100$ GeV, $h^R = 0.92$.
Furthermore, if $\sin 2\theta = 10^{-4}$, $h^L = 10^{-4}$, and $m_2 = 115$ GeV, then $m_\nu = 0.1$ eV.

SIDM Model with Z_4^L and Dark $Z_2 = R_\chi$

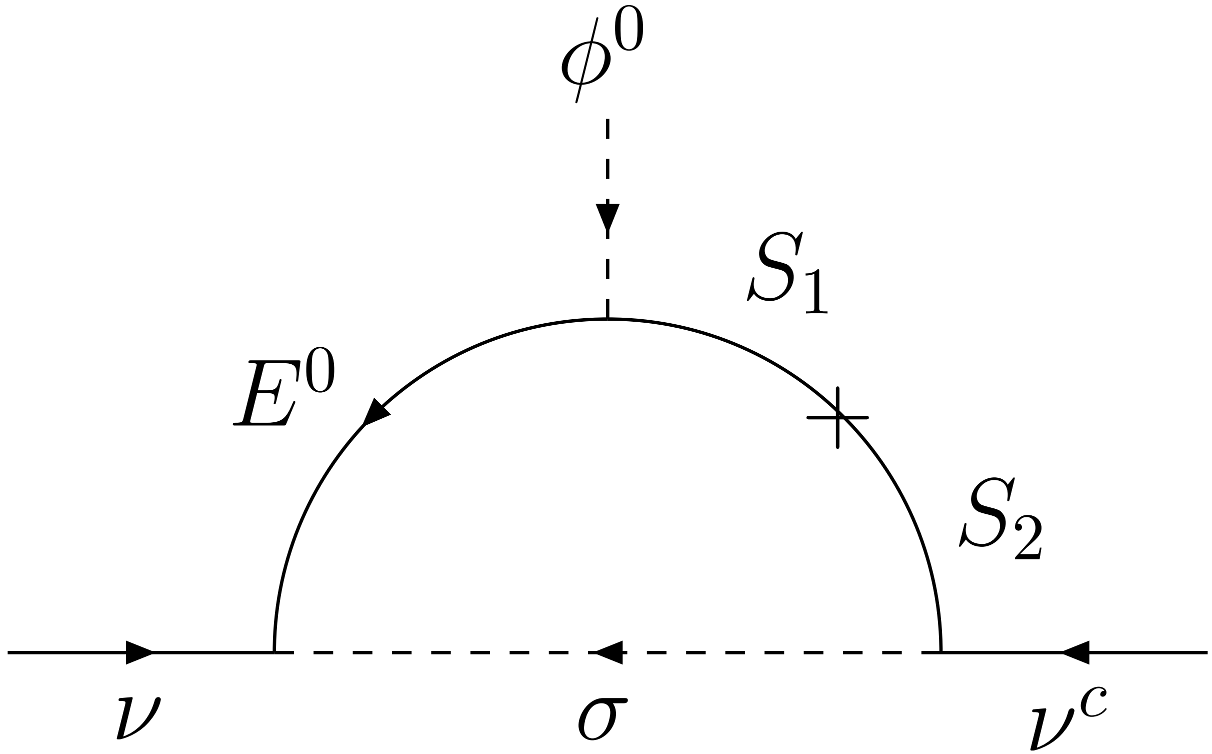
To understand the flatness of the central density profile of dwarf satellite galaxies (the cusp-core problem), the idea of SIDM (Self-Interacting Dark Matter) has been proposed. Typically, $\sigma_{el}/m_\chi \sim 1$ cm^2/g is needed, where χ is the dark matter and σ_{el} is the elastic scattering of χ with itself through the exchange of its mediator ζ. Typical mass ranges are $100 < m_\chi < 200$ GeV and $10 < m_\zeta < 100$ MeV.

Now ζ should decay, either from mixing with the Higgs boson or the $U(1)_Y$ gauge boson. After the freeze-out of

χ from its annihilation to ζ, as the Universe cools, the Sommerfeld enhancement of this cross section through the light ζ becomes much greater because χ is more at rest, and the subsequent decay of ζ to electrons and photons would disrupt the CMB (Cosmic Microwave Background) and be incompatible with observation [Bringmann/Kahlhoefer/Schmidt-Hoberg/Walia, PRL 118, 141802 (2017)]. This problem is evaded if ζ is stable [Ma, PLB 772, 442 (2017); Duerr/Schmidt-Hoberg/Wild, JCAP 1809, 033 (2018)] or if ζ decays only to two neutrinos [Ma/Maniatis, JHEP 1707, 140 (2017); Ma, MPLA 33, 1850226 (2018)].

Let the scalar doublet (η^+, η^0) be replaced by the fermion doublet (E^+, E^0), and the scalar singlet ζ be replaced by ζ', ζ'' and the fermion singlets $S_{1,2}$.

particle	$SO(10)$	$SU(2)$	$U(1)_Y$	$U(1)_\chi$	Z_2	Z_4^L	$Z_2^{(D)}$
(ν, e)	16	2	$-1/2$	3	$+$	i	$+$
ν^c	16	1	0	-5	$-$	$-i$	$+$
(E^+, E^0)	10	2	1/2	2	$-$	1	$-$
S_1	45	1	0	0	$-$	1	$-$
S_2	45	1	0	0	$+$	1	$-$
σ	16	1	0	-5	$-$	$-i$	$-$
ζ'	126	1	0	-10	$+$	-1	$+$
ζ''	2772	1	0	-20	$+$	1	$+$


ϕ^0
S_1
E^0
S_2
ν
σ
ν^c

The discrete Z_2 symmetry is imposed, under which all dimension-four terms must obey, and is softly broken only by the dimension-three $S_1 S_2$ term, whereas S_1^2 and S_2^2 are allowed Majorana mass terms. The $U(1)_\chi$ symmetry is broken by ζ'' and since it couples to $(\zeta')^2$ and ζ' couples to σ^2, the residual symmetry of this model is Z_4 which enforces the existence of Dirac neutrinos. The Z_4^L column of the table shows that $\nu \sim i$, $\zeta' \sim -1$, $\nu^c, \sigma \sim -i$, and others ~ 1. In addition, because of the restricted $U(1)_\chi$ couplings, $R_\chi = (-1)^{Q_\chi + 2j}$ is also conserved and acts as dark parity as discussed before.

In this one-loop model, σ may be chosen as dark matter. It is a pure singlet, whereas in the previous model it must mix with η^0 which is part of a doublet. Because of the $\zeta'\sigma\sigma$ interaction, it is SIDM. Now the interaction $(\zeta')^*\nu^c\nu^c$ is also allowed, so ζ' decays only to two neutrinos because of Z_4^L. This is then an explicit example of SIDM which is compatible with the CMB. It depends crucially on the Dirac nature of neutrinos.

It is possible that the two other astrophysical anomalies, i.e. the missing-satellite and too-big-to-fail problems, may also be solved, using the drag on dark matter by the cosmic neutrino background.

Concluding Remarks

In the framework of $SO(10) \to SU(5) \times U(1)_\chi$, dark matter and Dirac neutrino masses appear in a new light. There are several possible new insights in the scotogenic context. One such is the emergence of possible light Dirac fermion dark matter with conserved global lepton number, with either Z_3 or $U(1)$ for the dark symmetry. Another is self-interacting dark matter with a light scalar dilepton mediator which couples only to neutrinos, where lepton number is Z_4 and the dark parity is just $R_\chi = (-1)^{Q_\chi + 2j}$.