The coherent weak flavour charge of ordinary matter for neutrino-exchange forces

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Abstract. We study the long-range force arising between two aggregates of ordinary matter due to a neutrino-pair exchange, in the limit of zero neutrino mass. Even if matter is neutral of electric charge, it is charged for this weak force. The interaction is described in terms of a coherent charge, which we call the weak flavour charge of aggregated matter. For each one of the interacting aggregates, this charge depends on the neutrino flavour as

\[ Q_{\nu_e}^{W} = 2Z - N, \]
\[ Q_{\nu_\mu}^{W} = Q_{\nu_\tau}^{W} = -N, \]

where \( Z \) is the number of protons and \( N \) the number of neutrons. \( Q_{\nu_e}^{W} \) depends explicitly on \( Z \) because of the charged current contribution to \( \nu_e \) elastic scattering, while the \( N \) term in the three charges comes from the universal neutral current contribution. The effective potential describing this force is repulsive and decreases as \( r^{-5} \). Due to its specific behaviour on \((Z, N)\) and \( r \), this interaction is distinguishable from both gravitation and residual electromagnetic forces. As neutrinos are massive and mixed, this potential is valid for \( r \lesssim 1/m_\nu \).

1. Introduction
It’s been 86 years since Wolfgang Pauli postulated the existence of the neutrino in order to explain the continuous spectrum in \( \beta \)-decays, and 60 years since Reines and Cowan discovered it. In those years, we’ve learnt many properties about this particle, such as the fact that it only interacts through weak interactions—all of its charges but weak isospin are zero. In fact, in the framework of the Standard Model [1], there are only left-handed neutrinos, so Standard Model neutrinos are massless—we can’t generate a neutrino mass through a Yukawa-type coupling with a Higgs doublet.

Other interesting phenomena related to this particle are neutrino oscillations [2], which have been well established experimentally since 1998. This process is understood as the fact that there is a mismatch between mass eigenstates and flavour eigenstates, so that flavours get mixed along free propagation. Indeed, the observation of neutrino oscillations is a direct measurement of the mass difference between the three states, proving that neutrinos are massive particles, which is a first signal of Physics beyond the Standard Model.

Therefore, the study of the origin of neutrino mass is one of the directions in which we can expect finding new Physics, even though its small value \((m_\nu \lesssim 1 \text{ eV})\) makes it hard to observe experimentally. As well as determining the absolute mass of the neutrino, there’s still a more fundamental question about their nature unanswered: their finite mass could be explained through a Dirac mass term (implying there is a conserved total lepton number \( L \) distinguishing neutrinos from antineutrinos, which are described by 4—component Dirac spinors)
or through a Majorana one (implying that neutrinos are self-conjugate of all charges, described
by 2 independent degrees of freedom).

In any case, the fact that their masses are very low stands, and we discuss here another
property of neutrinos as mediators of a new force. As is well known, the processes represented
in Quantum Field Theory by the exchange of a massless particle give raise to long-range
interactions. An easy example is the scattering of two particles mediated by a photon, which—at
tree level—describes Coulomb scattering. Our objective in this work is the application of these
ideas to a process mediated by neutrinos. According to the Electroweak Lagrangian, the lowest-
order process is a neutrino-pair exchange, which—since neutrinos are nearly massless—describes
an interaction of long range.

2. Long-range weak interaction between aggregate matter

We are interested in obtaining the interaction potential due to a neutrino-pair exchange between
two matter aggregates, say $A$ and $B$. In doing so, we will not impose any restriction on the
internal structure of the aggregates—whatever they are, we only ask them to be neutral of
electric charge. Therefore, for each aggregate, its composition is specified by two numbers: $Z$
will represent the number of protons and the number of electrons, which must be the same, and
$N$ will represent the number of neutrons.

The picture is now clear. As represented in Fig.1, elastic interactions of matter constituents
with neutrinos is through either $W$ or $Z$ exchange. These fundamental interactions, as well as the
aggregate structure, determine the 1-loop neutrino-pair exchange $AB \rightarrow AB$ elastic interaction,
as shown in Fig.2.

The whole interaction potential between the two aggregates is given by the Fourier Transform
of the Feynman amplitude in Fig.2. Since we are only interested in the long-range part of
the potential, a few simplifications can be performed. Through rewriting the amplitude as
an unsubtracted dispersion relation, we find the long-range behaviour is fully determined by
its absorptive part. In turn, the absorptive part is determined, after unitarity-cutting the
diagram in the $t$-channel, by a simple tree-level $A\nu \rightarrow A\nu$ amplitude. This tree-level calculation
is straightforward—in the process, we only kept the dominant contributions, neglecting both
incoherent and relativistic corrections.

![Figure 1](image1.png)

**Figure 1.** Fundamental Electroweak elastic scattering between a neutrino and a matter
constituent ($e$: electron, $p$: proton, $n$: neutron).

![Figure 2](image2.png)

**Figure 2.** Effective neutrino-pair exchange interaction between two aggregates of matter. The blobs in
the vertices represent any structure the aggregates could have.
The analysis described above leads [4] to the interaction potential

\[ V(r) = \frac{G_F^2}{8\pi^3} \left[ (2Z_A - N_A)(2Z_B - N_B) + 2N_A N_B \right] \frac{1}{r^5}. \]  \hspace{1cm} (1)

3. Coherent weak flavour charges

A careful reading of Eq.(1) shows the standard structure of an interaction potential. By defining, for each of the aggregates, their weak flavour charges as \( Q_{W}^{\nu_e} = 2Z - N \) and \( Q_{W}^{\nu_{\mu}} = Q_{W}^{\nu_{\tau}} = -N \), one gets the usual structure \( V = \text{(coupling)}^2 \times \text{(product of charges)} \times \text{(power law)}. \)

Indeed, this shows that, within the Standard Model, matter is charged! The values of the weak charges of all stable atoms are represented in Fig.3. At this point, we remark that the unique \((Z,N)\) dependence of these charges makes them scale with the size of the system in a different way than gravitation. Also, the fact that the charges of all elements have the same sign (for each flavour) implies that this interaction is always repulsive. These two properties may become crucial in disentangling this weak interaction from gravitation experimentally.

![Figure 3. Weak flavour charges of the elements specified by the atomic number \( Z \), compared to their mass \( \approx Z + N \). The isotope chosen is the one in which the \((Z,N)\) pair lies in the valley of nuclear stability.](image)

4. Prospects

The long-range potential obtained in this work, Eq.(1), is valid and of interest for distances between nanometers and microns. The short-distance limit comes from the requirement of having neutral (of electric charge) systems of aggregate matter, while the long-distance limit is imposed by a non-vanishing value of the absolute mass of the neutrino—indeed, the range of this interaction for neutrinos of \( m \sim 0.1 \) eV is of the order of \( R \sim 1/m_{\nu} \sim 1\mu m. \) In this region, the effective potential will become of Yukawa type instead of the inverse power law.

The neutrino mass dependence of the effective potential in the long-range behaviour opens novel directions in the study of the most interesting pending questions on neutrino properties: absolute neutrino mass (from the range), flavour dependence and mixing (from the weak charges in the interaction) and, hopefully, with two neutrino exchange, the exploration of the most crucial open problem in neutrino physics: whether neutrinos are Dirac or Majorana particles.

Acknowledgements

The author acknowledges financial support from the Spanish Ministry of Education, Culture and Sports through the FPU14/04678 grant.

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