Neutrino masses from a three-quanton model with spin-spin force and its relation to the gravitational coupling \( G_N \)

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Abstract

Based on a generalisation of quantum electrodynamics with massless elementary fermions (quantons, \( q \)) and scalar coupling of gauge bosons, neutrinos are described as composite particles of \( q^o\bar{q}q^o \)-structure bound by a magnetic spin-spin interaction. Combining results from application of a vacuum potential sum rule with deduced mass square differences from neutrino oscillations, neutrino masses of about 0.015 eV, 0.017 eV, and 0.052 eV have been deduced for \( \nu_e \), \( \nu_\mu \), and \( \nu_\tau \), respectively. The electron has a similar \( q^o\bar{q}q^- \)-structure, leading to a direct relation between the masses of electron and \( \nu_e \), which is used as consistency test of the deduced neutrino masses.

The strength of the magnetic spin-spin interaction is found to be a factor \( \sim 10^{15} \) smaller than the 'electric' interaction between charged quantons. Together with the reduction of the coupling strength \( \alpha \) from microscopic systems to a distance of \( \sim 0.5 \) m by a factor of \( \sim 2 \cdot 10^{-24} \), the magnetic spin-spin coupling is consistent with the gravitational coupling \( G_N \). Thus, a unified description of fundamental forces appears possible.

PACS/keywords: 11.15.-q, 14.60.Pq, 14.60.Cd, 95.30.Sf/ Description of neutrinos as composite systems of elementary massless fermions (quantons \( q \)) bound by a magnetic spin-spin force. Deduced masses of neutrino flavour states. Consistency of the deduced magnetic spin-spin force with the gravitational constant \( G_N \).

The observation of neutrino oscillations has given clear evidence that neutrinos are massive and have finite transition probabilities between different flavour states. The masses illuminate in a new way the open mass problem in the Standard Model (SM), see ref. [1].
which the generation of mass by the Higgs mechanism \[2\] does not lead to Dirac neutrinos \((\nu \neq \bar{\nu})\), important for the understanding of the properties of the weak interaction. Both, finite mass and transitions between states are characteristic of composite systems, therefore, in the present paper neutrinos are described as systems of three massless elementary fermions (quantons) bound by a magnetic spin-spin force.

We use a generalisation of quantum electrodynamics \[3\] (quanton model), which leads to a good understanding of the confinement potential in mesons. Also the flavour degree of freedom in mesons is well understood \[4\], which exists in a similar way in leptons. Interestingly, in this formalism the coupling strength \(\alpha\) is not constant but falls off with the size of the system; therefore it appears possible that this model can be applied to other fundamental forces.

Different from the application to non-charged mesons composed out of charged quantons \(q^+\) and \(q^-\), non-charged quantons \(q^o\) and \(\bar{q}^o\) are involved in neutrinos, which are bound by a magnetic force, which acts on the spins of the quantons. The structure of \(q^o\) may be viewed as an elementary magnetic dipole with spin=1/2 pointing in the direction of motion, for \(\bar{q}^o\) the spin is directed in the opposite way; so \(q^o \neq \bar{q}^o\). Neutrinos and antineutrinos are assumed of \((q^o \bar{q}^o q^o)\) and \((q^o \bar{q}^o \bar{q}^o)\) structure, respectively, with interactions conserving CP invariance.

The Lagrangian is of the form

\[
\mathcal{L} = \frac{1}{m^2} \bar{\Psi}^o i\gamma^\mu \partial^\mu (D^\nu D^\nu) \Psi^o - \frac{1}{4} F_{\mu
u} F^{\mu
u},
\]  

(1)

where \(\Psi^o\) is an elementary noncharged quanton spinor field and \(D^\mu\) the covariant derivative \(D^\mu = \partial^\mu - ig_m A^\mu\) with elementary boson fields \(A^\mu\) and magnetic coupling \(g_m\), which is many orders of magnitude smaller than the electric coupling \(g_e\) between charged quantons. Further, \(F_{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu\) is the Abelian field strength tensor.

Analogue to the derivation in ref. \[3\] the Lagrangian \[1\] gives rise to two first-order matrix elements between quantons

\[
\mathcal{M}_{2g} = -\alpha_m^2 \frac{1}{m^3} \bar{\psi}(\tilde{p}) \gamma^\mu \gamma^\nu \partial^\rho w(q) g_{\mu\rho} \gamma^\rho \psi(\tilde{p})
\]

(2)

and

\[
\mathcal{M}_{3g} = -\alpha_m^3 \frac{1}{m} \bar{\psi}(\tilde{p}) \gamma^\mu w(q) \frac{g_{\mu\rho} f(p_i)}{p_i^2} w(q) \gamma^\rho \psi(\tilde{p})
\]

(3)
in which \( \alpha_m = g_m^2/4\pi \), \( \psi(\tilde{p}) \) is a two-fermion wave function \( \psi(\tilde{p}) = \frac{1}{m^*} \Psi^0(p) \Psi^0(k) \) and \( w(q) \) the momentum distribution of two overlapping boson fields. The momenta have to respect the condition \( \tilde{p}' - \tilde{p} = q + p_i = P \). Further, \( f(p_i) \) is the probability to combine \( q \) and \( P \) to \( -p_i \). Since \( f(p_i) \to 0 \) for \( \Delta p \to 0 \) and \( \infty \), there are no divergencies in \( M_3 \).

From \( M_{2g} \), by contracting the \( \gamma \) matrices to \( g_{\mu\rho} = \frac{1}{2} (\gamma_\mu \gamma_\rho + \gamma_\rho \gamma_\mu) \) and making a reduction to three dimensions as in ref. [3], a potential is obtained, which is given in r-space by spherical coordinates

\[
V_{2g}(r) = \frac{\alpha_m^2 \hbar^2 \tilde{E}^2}{m^3} \left( \frac{d^2 w(r)}{d r^2} + \frac{2}{r} \frac{d w(r)}{d r} \right) \frac{1}{w(r)},
\]

where \( \tilde{E} = <E^2>^{1/2} \) is the mean energy of the scalar states of the system and \( w(r) \) the two-boson wave function (Fourier transform of \( w(q) \) in eq. (2)).

\( M_{3g} \) could give rise to a tensor potential \( V_{\sigma_1 \sigma_2} \) between the quanton spins by contracting the \( \gamma \) matrices to the tensor \( \sigma_{\mu\rho} = i \frac{1}{2} (\gamma_\mu \gamma_\rho - \gamma_\rho \gamma_\mu) \). However, in the matrix elements [2] and [3] the \( \gamma \) matrix indices \( \mu \) and \( \rho \) can be chosen arbitrarily; so, the combinations \( \gamma_\mu \gamma_\rho \) and \( \gamma_\rho \gamma_\mu \) are equally possible, leading to a cancellation of the tensor component. Therefore, we have to assume the same contraction of the \( \gamma \) matrices as for the matrix elements between charged quantons, see ref. [4], leading also to vector boson propagation in \( M_{3g} \). Consequently, the quanton-boson coupling depends only on the charge or spin coupling constants \( \alpha_e \) or \( \alpha_m \), or their mixing \( \sqrt{\alpha_e \alpha_m} \) in case of a coupling of electric and magnetic fields. This assumption is tested below by comparing bound state potentials and masses for \( \nu_e \) and the electron, the latter being of three quanton structure \( q^o \bar{q}^o q^- \).

With a reduction of the matrix element \( M_{3g} \) to three dimensions we obtain the boson-exchange potential

\[
V_{3g}(r) = \frac{\hbar}{m} \int d r' \rho(r') \ V_m(r - r'),
\]

in which \( \rho(r) \) is the two-boson density \( \rho(r) = w^2(r) \) (with dimension \( fm^{-2} \)) and \( V_m(r) \) a boson-exchange interaction between neutral quantons \( V_m(r) = -\alpha_m^3 \hbar \frac{f(r)}{r} \) within the two-boson field. Since the quanton-antiquantum parity is negative, the potential (5) corresponds to a binding potential for vector states. For scalar states (which have stronger binding) angular momentum \( L=1 \) is needed, consequently, a p-wave density is required in eq. (5) which is related to the spherical density \( \rho(r) \) by

\[
\rho^p(\vec{r}) = \rho^p(r) 
Y_{1,m}(\theta, \Phi) = (1 + \beta R \ d/dr) \rho(r) 
Y_{1,m}(\theta, \Phi).
\]

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\( \beta R \) is determined from the condition \( < r_{p^\circ} > = \int d\tau \ r \rho^p(r) = 0 \). This yields a boson-exchange potential given by

\[
V_{3g}^p(r) = \frac{4\pi \hbar}{m} \int dr' \rho^p(r')V_m(r - r') .
\] (7)

Further, applying the very important matching condition \( V_{3g}^p(r) = c_{pot} \rho(r) \), see ref. [3], we can use \( V_m(r) \) of the form \( V_m(r) = f_{as}(r)(-\alpha_3^m \hbar /r) \ e^{-cr} \) with \( f_{as}(r) = (e^{ar} - 1)/(e^{ar} + 1) \). This yields self-consistent densities of the form \( \rho(r) = \rho_o \left[ \exp\left\{ -(r/b)\kappa \right\}\right]^2 \). A very weak coupling strength \( \alpha_m \) is needed to get small neutrino masses. This gives rise to a density \( \rho(r) \) with a very small radius \( < 10^{-4} \text{ fm} \).

Results for a mean square radius \( < r_{p^2} > \) of 0.15 \( 10^{-8} \text{ fm}^2 \) are given in fig. 1, which displays in the upper part the effective interaction \( V_m(r) \) (solid and underlying dashed line) together with the low radius cut-off function \( f_{as}(r) \) (dashed line), which shows \( f_{as}(r) \to 0 \) for \( r \to 0 \). By Fourier transformation to Q-space this yields \( f_{as}(Q) \to 0 \) for \( Q \to \infty \), a property so far known only of the strong interaction, see ref. [3]. This is equivalent to asymptotic freedom in quantum chromodynamics [5]. In the lower two parts quanton density \( \rho_q(r) \) and boson-exchange potential (7) are given in r- and Q-space, which show good agreement. Importantly, different from the interaction between quanton charges, the force between their spins is always attractive, since integration over all orientations of spin yields the same contributions for \( q^o \) and \( \bar{q}^o \). Therefore, the total boson-exchange potential is given by a sum of the three \( q^o \) potentials \( V_{q^2}^{qq}(r) = 2 \ V_{q^o q^o}(r) + V_{q^o \bar{q}^o}(r) \) = 3 \( V_{q^o q^o}(r) \). Evaluation of the potential \( V_{2g}(r) \) in eq. (4) yields results given in fig. 2. The form of the potential is similar to the confinement potential in hadrons, ensuring also that leptonic three-quanton states are confined.

Lowest bound state energies \( E_{2g} \) and \( E_{3g} \) have been calculated from \( V_{2g}(r) \) and \( V_{3g}(r) \), respectively, giving rise to a mass \( M = -E_{3g} + E_{2g} \). For these calculations a mass parameter \( \bar{m} = 1/4 < Q_{\rho}^2 >^{1/2} \) was used. \( \bar{E} \) is then consistent with \( \bar{E} \sim < Q_{\rho}^2 >^{1/6} Q_o^{4/6} \) (with \( Q_o = 1 \text{ GeV} \)), but with seizable uncertainties.

To get discrete solutions, which describe different flavour states, a vacuum potential sum rule similar to that in ref. [4] is applied

\[
V_{vac}(r) = \sum_i \ V_{3g}^i(r) = \bar{f}_{as}(r)(-\bar{\alpha}_m^3 \hbar /r_o/r^2) \ e^{-cr} , \tag{8}
\]
Table 1: Deduced neutrino masses, mean radii squares and average values of $Q$ for the three lowest self-consistent solutions.

| Neutrino | mass (eV) | $<r^2_\rho>$ (fm$^2$) | $<r^2_{\bar{\nu}_m}>$ (fm$^2$) | $<Q^2_{\bar{\nu}}^{1/2}$ (GeV) |
|----------|-----------|-------------------|-------------------|-------------------|
| $\nu_e$  | 0.0150    | 0.15 $10^{-8}$    | 0.19 $10^{-8}$    | 12670             |
| $\nu_\mu$ | 0.01735  | 0.67 $10^{-9}$    | 0.91 $10^{-9}$    | 21050             |
| $\nu_\tau$ | 0.0520   | 0.21 $10^{-9}$    | 0.25 $10^{-9}$    | 37860             |

where $\hat{f}_{as}(r)$ and $e^{-\tilde{c}r}$ are cut-off functions as used for $V_m(r)$ with parameters $\tilde{a}$, $\tilde{\sigma}$, and $\tilde{c}$ close to the corresponding values of the lowest energy solution. From the sum rule (8) bound state solutions are obtained with increasing relative mass, however, there could be rather large uncertainties in the absolute masses. Therefore, absolute neutrino masses are deduced in the following by combining masses obtained from the sum rule (8) together with experimentally determined neutrino mass square differences.

From neutrino oscillation experiments [6] the following neutrino mass square differences have been deduced

$$\Delta m^2_{\text{sol}} \simeq 7.6 \ 10^{-5}(eV)^2,$$

$$\Delta m^2_{\text{atm}} \simeq 2.4 \ 10^{-3}(eV)^2.$$

Consistent with the sum rule (8) these results have to be related to the neutrino masses as follows: $\Delta m^2_{\text{sol}} = m^2_{\nu_\mu} - m^2_{\nu_e}$ and $\Delta m^2_{\text{atm}} = m^2_{\nu_\tau} - m^2_{\nu_\mu}$.

The sum rule (8) predicts a mass of $\nu_\mu$ somewhat larger but much less than twice that of $\nu_e$. Further, $\nu_\tau$ can be significantly heavier with a mass spacing which depends strongly on the radial extent of the neutrino system. This is related to the average momentum $\bar{Q}$ of the two-boson densities. In an attempt to find solutions, which fulfill both, the sum rule (8) and the relations (9) and (10), results have been obtained, which are given in table 1 (with the parameters in table 2). These give rise to boson-exchange potentials (7) shown in fig. 3, which yield a satisfactory description of the sum rule (8). Since the overall strength $\tilde{\alpha}_m^3 \hbar r_o = 0.44 \ 10^{-20}$ leads to $\tilde{\alpha}_m$ in the same order as $\alpha_m$ of the three solutions, this gives us confidence that the deduced masses are quite correct. The good agreement with the sum rule is clear evidence - like in the case of hadrons [4] - that the flavour states are eigenstates of the neutrino system. The radial overlap of the different
Table 2: Deduced density parameters and coupling strength $\alpha_m$ for the three self-consistent solutions in table 1.

| Neutrino | $\kappa$ | $b$ (fm) | $c$ (fm$^{-1}$) | $a$ (fm$^{-\sigma}$) | $\sigma$ | $\alpha_m$ |
|----------|---------|---------|-------------|----------------|---------|-----------|
| $\nu_e$  | 1.31    | 3.28 $10^{-5}$ | 6.0 $10^4$  | 2.5 $10^4$   | 0.86    | 0.46 $10^{-5}$ |
| $\nu_\mu$| 1.30    | 2.11 $10^{-5}$ | 8.8 $10^4$  | 3.4 $10^4$   | 0.86    | 0.48 $10^{-5}$ |
| $\nu_\tau$| 1.29   | 1.13 $10^{-5}$ | 1.7 $10^5$  | 6.0 $10^4$   | 0.86    | 0.62 $10^{-5}$ |

The sum of neutrino masses is about 30% of the upper bound of 0.28 eV determined from astrophysical observations \textsuperscript{[7]}. In fig. 3 we see that the vacuum sum rule (8) is in quantitative agreement with the sum of neutrino potentials for radii above $10^{-5}$ fm (upper part). However, at lower radii a deviation from the sum rule is observed (see lower part), which could be an indication for another neutrino $\nu_\kappa$ of a much larger mass of $m_{\nu_\kappa} > 0.1$ eV. However, this neutrino is expected to decay very fast and will therefore be difficult to detect.

From the results in table 1 we can deduce the strength ratio $R_{e/m}$ of the magnetic spin-spin interaction to the electric Coulomb force, which is given by the ratio of the deduced mass to $<Q^2>^{1/2}$. From this we obtain $R_{m/e} \sim 10^{-15}$.

As a serious test of our method, a comparison of the mass of $\nu_e$ is made with the electron, which has a mass larger by a factor of $3.4 \times 10^7$. The only structural difference in the quanton model is that one neutral quanton of $\nu_e$ is replaced for $e$ by a charged one. Consequently, two $q^o - q^o$ potentials \textsuperscript{[4]} and \textsuperscript{[5]} have to be changed to $q^+ - q^o$ potentials, with magnetic coupling constant $\alpha_m$ replaced by an electro-magnetic coupling $\sqrt{\alpha_e \alpha_m}$. Inserting the latter coupling without any other changement of parameters yields a mass of the electron of 0.4 MeV, which is not much different from the experimental mass $m_e = 0.51$ MeV. By a slightly smaller neutrino mass the electron mass is improved, but changes of the radius yields similar effects. Nevertheless, this rather good result, which involves bound state calculations with energy differences of seven orders of magnitude, gives us confidence that the neutrino masses and the strength of the magnetic spin-spin force are well extracted.

Since the magnetic spin-spin interaction is fifteen orders of magnitude smaller than the
Table 3: Estimated coupling strength \((\alpha^{0.5m})^3\) extrapolating from different microscopic systems. Radius square in fm\(^2\), and \(\bar{Q}\) and masses in GeV. The calculations for mesons are discussed in ref. [4].

| System | (mass) | \(< r_q^2 >\) | \(\bar{Q}\) | \(X\) | \((1/X)M\) | \((\alpha^{0.5m})^3\) |
|--------|--------|---------------|-------------|------|-------------|------------------|
| small  | (–)    | 0.11 \(10^{-7}\) | 5068        | 4.83 \(10^{18}\) | 1.05 \(10^{-15}\) | 1.99 \(10^{-24}\) |
| small  | (–)    | 0.25 \(10^{-6}\) | 993.0       | 9.96 \(10^{17}\) | 9.968 \(10^{-16}\) | 2.05 \(10^{-24}\) |
| \((t\bar{t})\) | (91.2) | 0.256 \(10^{-4}\) | 102.4       | 9.88 \(10^{16}\) | 9.177 \(10^{-16}\) | 2.90 \(10^{-24}\) |
| \(\Upsilon\) | (9.46) | 0.174 \(10^{-2}\) | 11.35       | 1.20 \(10^{16}\) | 7.890 \(10^{-16}\) | 2.57 \(10^{-24}\) |
| \(J/\Psi\) | (3.098) | 0.115 \(10^{-1}\) | 4.40        | 4.66 \(10^{15}\) | 6.642 \(10^{-16}\) | 2.27 \(10^{-24}\) |
| \(\Phi\) | (1.02) | 0.10           | 1.50        | 1.57 \(10^{15}\) | 6.57 \(10^{-16}\) | 2.80 \(10^{-24}\) |
| \(\omega\) | (0.78) | 0.23           | 0.96        | 1.04 \(10^{15}\) | 7.47 \(10^{-16}\) | 3.11 \(10^{-24}\) |

electric Coulomb interaction between quantaons, it is challenging to ask, whether this force may be responsible also for gravitation. The gravitational force is extremely weak with a gravitational coupling \(G_N = 6.707 \times 10^{-39} \, \hbar \, [\text{GeV}/c^2]^{-2}\), measured for distances between 1cm and 1m.

In our formalism the coupling \(\alpha\) depends on the size of the system, therefore, for the investigation of this problem an extrapolation of the coupling strength to a distance of 0.5 m on the average, \(\alpha^{0.5m}\), is needed. The actual coupling strength is not \(\alpha\) but \(\alpha^3\), so we have to determine \((\alpha^{0.5m})^3\). This has been done by a scaling method: for a given density the mean square radius \(R =< r_q^2 >^{1/2}\) is scaled to 0.5 m, \(R \rightarrow XR\). Then, the scaling of \(\bar{Q} =< Q^2 >^{1/2}\) is \(\bar{Q} \rightarrow (1/X)\bar{Q} \sim (1/X)M\). The remaining task is to determine the coupling \((\alpha^{0.5m})^3\) which gives rise to a bound state with mass \((1/X)M\) (with contributions both from \(V_{2g}(r)\) and \(V_{3g}(r)\)). We obtain a quite large spread of values dominated by uncertainties in the deduced value of \(\bar{E}\). In order to get more reliable results, we made extrapolations starting from several systems of quite different size as indicated in table 3. Then, the two-boson density parameter \(\kappa\) and the Q-dependence of \(\bar{E}\) were varied. Changes of \(\kappa\) had very little effect, however, the Q-dependence of \(\bar{E}\) had a strong influence on the deduced value of \(\alpha^{0.5m}\). With a dependence \(\bar{E} = < Q^2 >^{1/4} Q_o^{1/2}\) (with \(Q_o=1\) GeV), results were obtained, which are given in table 3. These show a rather small spread with an average coupling strength \((\alpha^{0.5m})^3\) of \(2.5 \times 10^{-24}\).
The magnetic coupling strength at 0.5 m can now be estimated by the relation $(\alpha_{0.5m}^m)^3 = (\alpha_{0.5m}^m)^3 R_{m/e} \sim 2.5 \times 10^{-39}$. $G_N$ is given by $G_N = (\alpha_{0.5m}^m)^3/m_1 m_2$, where $m_i$ is given roughly by the nucleon mass, which is the heaviest constituent of matter. Inserting this, we obtain $G_N \sim 3 \times 10^{-39}\hbar [\text{GeV}/c^2]^{-2}$, which is in surprisingly good agreement with the experimental value of $6.707 \times 10^{-39}\hbar [\text{GeV}/c^2]^{-2}$.

In conclusion, neutrino masses have been calculated as bound states of $q_0 \overline{q}_0 q_0$-states mediated by a magnetic spin-spin interaction between quantons. This interaction is about $10^{-15}$ times weaker than the Coulomb interaction between charged quantons, consequently the mass and radius of neutrinos is very small. It should be emphasized, that neutrinos are the only probe, by which the weak spin-spin interaction could be determined with reasonable precision. The good understanding of the relative electron and $\nu_e$ masses can be considered as an excellent confirmation of our model and gives us confidence that the neutrino masses are well extracted.

An extrapolation of the coupling constant $\alpha_m^3$ to macroscopic distances yields values consistent with the gravitational coupling $G_N$, which may indicate that the gravitational force can be interpreted as magnetic interaction between quantons in matter. Since in our model mass is given by binding energies, there is no problem with the energy density of the universe deduced from astrophysical observations. This is in contrast to the Standard Model, in which the Higgs-mechanism requires an enormous energy density of the universe (known as cosmological constant problem).

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Figure 1: Self-consistent for $\nu_e$. Upper part: Low radius cut-off function $f_{as}(r)$ and shape of $V_m(r)$ given by dashed and solid lines, respectively. Lower two parts: Two-boson density and boson exchange potential $|V_{3g}/c_{pot}|$ given by the overlapping dot-dashed and solid lines, respectively, in r- and Q-space.
Figure 2: Deduced confinement potential $V_{2g}(r)$ (solid line) and shape of the density (dot-dashed line) for $\nu_e$. 
Figure 3: Boson-exchange potentials $V_{3g}(r)$ for the solutions in table 1 (given by dot-dashed and dashed lines) with their sum given by solid line. This is compared to the vacuum potential sum rule $V = -\text{const}/r^2$ given by the dot-dashed line overlapping the solid line. A pure potential $V = -\text{const}/r^2$ is shown also by the lower dot-dashed line. Upper and lower part show the same results with a different scaling of the y-axis; the deviation of the solid and overlapping dot-dashed lines in the lower part may be indicative of a new solution with a significantly larger mass.