Weak interactions effect on the *p–n* mass splitting and the principle of equivalence

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Abstract

The weak interaction contribution to the proton–neutron mass difference is computed using a generalization of Cottingham's formula. When included in the analysis of the Eötvös experiment, this contribution reduces the bound on a possible weak interactions violation to the equivalence principle by one order of magnitude. © 2002 Elsevier Science B.V. All rights reserved.

1. Introduction

The Principle of Equivalence is the physical basis of General Relativity. It loosely states that any freely falling reference frame is locally equivalent to an inertial reference frame [1]. This is a very strong statement: its unrestricted validity leads to General Relativity as the unique theory for the gravitational field [2] and experimental tests of its consequences probe deeply the structure of gravitation.

The validity of the equivalence principle has been studied in the weak interaction sector, both from neu-

trino oscillations [3,4] and $K_0 - \overline{K}_0$ physics [5,6]. In either of the leptonic and mesonic sectors of the standard model, the bounds found for the breakdown of the equivalence principle are much smaller than those found in the baryonic sector. However, it is important to study the baryonic sector since the equivalence principle may be well satisfied for ultrarelativistic neutrinos and kaons while being violated by the weakly interacting non-relativistic baryons.

In this case, we must turn to one of the consequences of the equivalence principle, namely, the Universality of Free Fall (UFF), which states that the world line of a test body submerged in a gravitational field is independent of its composition and structure [7]. In order to clarify the former statement, let us write the Lagrangian of a test body in the non-relativistic approximation in the form [8]:

$$L = -m_R c^2 + \frac{1}{2} m_I \mathbf{v}^2 - m_P \phi(\mathbf{x}) + O\left(\frac{v^4}{c^4}\right), \qquad (1)$$

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where **v** and **x** are the velocity and the coordinate of the center of mass of the test body, ϕ is the gravitational potential and the parameters m_R, m_I and m_P are called, respectively, the rest, inertial and passive gravitational masses for the test body. UFF implies the equality of inertial and passive gravitational masses:

$$m_I = m_P \tag{2}$$

while Local Lorentz Invariance (LLI)—another consequence of the equivalence principle—implies the additional equality:

$$m_R = m_I. \tag{3}$$

UFF, among the consequences of the equivalence principle, is one of the strongest tests of its validity. For instance, it has been shown that sufficiently sensitive related experiments can provide strict tests on superstring theories (see, e.g., [9]) or Kaluza–Klein theories (e.g., [10]), thus exhibiting the presence of "new physics". Indeed, the STEP satellite experiment [11,12] will improve these tests sensitivity by about six orders of magnitude.

One of the profound consequences of the equivalence principle is that all forms of non-gravitational energy, since they contribute to the inertial mass, should couple in the same way to the gravitational field. Any violation of UFF should break equation (2) and the difference between inertial and passive gravitational mass of a test body could be expressed via phenomenological parameters Γ_t specific to each type of interactions t reflecting its degree of violation to the equivalence principle:

$$m_P - m_I = \delta m = -\sum_t \Gamma_t E^t, \tag{4}$$

where the nuclear binding energies E^t can be estimated using the semiempirical mass formula [13] or, in the case of weak interactions, a suitable generalization [14,15]. In principle, the parameters Γ_t are measured in Eötvös-like experiments where they are fitted to data, but they can also be predicted in some given theories of gravitation, thus providing a sensitive test of such theories.

Eötvös experiments [7,16–18] set an upper limit on the difference of acceleration in a gravitational field for different materials and so impose upper bounds on the violation parameters Γ_t. While most published estimates, taking into account only the binding energy contribution to the nucleus mass, show that strong and electromagnetic interactions obey the equivalence principle to an accuracy better than 10^{-8} [7,17], the upper bound on any violation of the equivalence principle by the weak interactions is much higher (10^{-2}) [7,17]. This is not only due to the tiny contribution of weak interactions to the total mass but also largely because the binding energy per nucleon due to weak interactions is a very slowly varying function across the periodic table which then leads to a large cancellation in the analysis of Eötvös experiments [14,15]. Although the weak interactions sensitivity can be improved by comparing elements which are as far apart as is possible in the periodic table, this slow variation will destroy the accuracy obtained in any experimental test of UFF.

In order to examine further the present accuracy of Eötvös experiments with respect to weak interactions, one should include the individual nucleons contribution to the nucleus mass since it changes much faster along the periodic table. There has not been, to our knowledge, a study of the weak interactions effect within nucleons in the analysis of Eötvös experiments and the object of this Letter is to provide just such a study. We shall evaluate the proton–neutron mass difference due to weak interactions and reassess the Eötvös experiments results.

There is a model-independent approach to the weak contribution to the nucleon mass difference consisting of the development of a sum rule that gives the nucleon self mass in terms of observable quantities. We shall call this approach the generalized Cottingham's formula since it was first done by Cottingham for the electromagnetic interactions [19]. This sum rule is a rigorous model-independent way for computing the proton–neutron mass difference. We describe very briefly this approach in Section 2 while we develop the generalized Cottingham's formula corresponding to the weak interactions in Section 3. In Section 4 we implement the weak p–n mass splitting result in a re-analysis of Eötvös experiments' results and find that they lead to an improved upper bound in that weak interactions violation of the equivalence principle is less than 10^{-3}.

2. The proton–neutron mass difference

One of the most interesting results in basic quantum field theory is that the proton–neutron mass difference is finite and can be computed, in principle, from experimental data. The method is due to Cottingham [19] and has been generalized to strong interactions [20,21]. In this section, we shall recall the main steps in the derivation of Cottingham's formula. Detailed proofs can be found in references [19,20,22].

To first order in the fine structure constant, the electromagnetic contribution to the self-energy of the nucleon may be written as:

$$\Delta M_N^{\mathrm{em}} = \frac{ie^2}{2(2\pi)^4} \int d^4q \, G_{\mathrm{em}}^{\mu\nu}(q^2) T_{\mu\nu}^{\mathrm{em},N}(\mathbf{q}, q_0), \quad (5)$$

where $G_{\mathrm{em}}^{\mu\nu} = \eta^{\mu\nu}/q^2$ is the photon propagator and $T_{\mu\nu}^{\mathrm{em},N}(\mathbf{q}, q_0)$ is the Compton scattering amplitude of a virtual photon with momentum q by a nucleon N at rest. In the Born approximation this amplitude reduces to:

$$
\begin{aligned}
&T_{\mu\nu}^{\mathrm{em},N}(\mathbf{q}, q_0) \\
&= \frac{(2\pi)^4}{2} \frac{4Mq^2}{q^4 - 4M^2 q_0^2} \left(1 + \frac{q^2}{2M^2}\right) \\
&\quad \times \sum_{\mathrm{spin}} \big[\langle N | J_\mu^{\mathrm{em}}(0) | N' \rangle \\
&\qquad\qquad \times \langle N' | J_\nu^{\mathrm{em}}(0) | N \rangle + \mu \leftrightarrow \nu \big],
\end{aligned} \quad (6)
$$

where M is the mass of the nucleon N at rest, N' indicates a nucleon with four-momentum $(\mathbf{q}, q_0 + M)$ and the sum is over both its spin states.

In the same approximation, the electromagnetic current matrix elements between two nucleons of momentum p, $p + q$ and spin α and α' can be expressed in the form:

$$
\begin{aligned}
&\langle N(p, \alpha) | J_\mu^{\mathrm{em}}(0) | N'(p+q, \alpha') \rangle \\
&= \bar{u}^{(\alpha)}(p) \big[F_1^N(q^2) \gamma_\mu + i F_2^N(q^2) \sigma_{\mu\nu} q^\nu \big] \\
&\quad \times u^{(\alpha')}(p+q),
\end{aligned} \quad (7)
$$

where $u(p)$ are Dirac spinors and F_1, F_2 are the Dirac and Pauli form factors of the nucleon.

Plugging (7) into (6) and doing a Wick rotation, one can get, after some algebra, the expression for the electromagnetic nucleon self energy:

$$
\begin{aligned}
\Delta M_N^{\mathrm{em}} = -\frac{1}{\pi} \int_0^\infty \frac{q\,dq}{q^2} \int_0^q dv \sqrt{q^2 - v^2} \frac{4Mq^2}{q^4 + 4M^2 v^2} \\
\times \big[3q^2 f_1(q^2) - (q^2 + 2v^2) f_2(q^2) \big], \quad (8)
\end{aligned}
$$

where the quantities $f_1(q^2)$, $f_2(q^2)$ can be written in terms of the electromagnetic Sachs form factors $G_{E,M}^N$ of the nucleon:

$$f_1(q^2) = \frac{\alpha}{\pi} \frac{G_M^2(q^2) - G_E^2(q^2)}{q^2 + 4M^2}, \quad (9)$$

$$f_2(q^2) = \frac{\alpha}{\pi} \frac{q^2 G_M^2(q^2) + 4M^2 G_E^2(q^2)}{q^2(q^2 + 4M^2)} \quad (10)$$

while, in turn, the Sachs form factors are expressed in terms of the Dirac and Pauli form factors via

$$G_E(q^2) = F_1(q^2) + \frac{q^2}{4M^2} F_2(q^2), \quad (11)$$

$$G_M(q^2) = F_1(q^2) + F_2(q^2). \quad (12)$$

The Sachs form factors, which can be measured from e-nucleon scattering data, have a simple physical interpretation in that they are closely related to the Fourier transforms of the nucleon charge and magnetic moment densities, respectively.

Eq. (8) with (9) and (10) is the celebrated Cottingham's formula. It expresses the electromagnetic contribution to the nucleon self mass as a weighted integral on the observable form factors and the results are finite, due to the fast decrease of the measured G_i. The electromagnetic contribution to the proton–neutron mass difference is obtained by subtracting the two electromagnetic self masses of the proton and the neutron $\Delta M_{p-n}^{\mathrm{em}} = \Delta M_p^{\mathrm{em}} - \Delta M_n^{\mathrm{em}}$. Using the "Galster parameterization" [23,24] for the electromagnetic form factors, a numerical integration results in:

$$\left(\frac{M^n - M^p}{M}\right)^{\mathrm{em}} = -8.3 \times 10^{-4} \quad (13)$$

which amounts to a nucleon mass difference of -0.79 MeV making the proton heavier than the neutron.

In the same way, the "strong" contribution to proton–neutron mass difference can be traced to ρ–ω mixing [20] or computed assuming certain models such as Skyrme models [25,26], chiral solitonic

models [27] and Sigma models [28]. In [20], an equation of the form (8) was established for the mass difference, in terms of the strong ρNN, ωNN and the ρ–ω mixing parameter ϵ, with the result:

$$\left(\frac{M^n - M^p}{M}\right)^{\mathrm{st}} = 2.22 \times 10^{-3} \tag{14}$$

which is equivalent to a mass difference of 2.08 MeV. The final result is the sum of (13) and (14):

$$\left(\frac{M^n - M^p}{M}\right)^{\mathrm{tot}} = 1.39 \times 10^{-3} \tag{15}$$

equivalent to a mass split of 1.31 MeV in excellent agreement with the experimental value 1.35 MeV. A careful error analysis of these results can be found in Ref. [22].

The above results are valid in the Born approximation, i.e., the lowest order in α while higher order corrections to the Cottingham formula are divergent and must be properly renormalized. However, following [29] for a careful discussion of this renormalization, we can see that the corrections to the mass difference, which depend on the renormalization point μ, are very small and have no practical importance. This is because the mass differences between particles belonging to the same isospin multiplet are finite in the chiral limit $m_q = 0$ and all the corrections introduced through counter terms are of the order of $O(m_q/M)$, smaller than experimental errors. The same situation occurs with respect to the breakdown of isospin symmetry and other similar higher order effects.

3. Analysis of the weak p–n mass splitting

In this section, we shall derive a weak Cottingham's formula to express the weak p–n mass splitting value in terms of experimental weak form factors.

Our starting point is the formula for the four-fermion interaction as a low energy approximation to the IVB theory corresponding to exchange of (W^+, W^-, Z^0) bosons:

$$\mathcal{L}^{\mathrm{eff}} = \mathcal{L}^{\mathrm{eff}}_{\mathrm{cc}} + \mathcal{L}^{\mathrm{eff}}_{\mathrm{nc}}$$
$$= \frac{-g^2}{2M_W^2} J^+_\mu J^{-\mu} + \frac{-g^2}{2M_W^2} J^N_\mu J^{N\mu}, \tag{16}$$

where, restricting our attention to one family of fermions, the charged current is given by

$$J^+_\mu = J^{+V}_\mu - J^{+A}_\mu$$
$$= \frac{1}{2} \sum_{f=\nu,e,u,d} \bar{f}\gamma_\mu(1 - \gamma_5)T^- f,$$
$$J^-_\mu = \left(J^+_\mu\right)^\dagger \tag{17}$$

and the neutral current is given by

$$J^N_\mu = \frac{1}{2} \sum_{f=\nu,e,u,d} \big[\bar{f}\gamma_\mu\big(T_3 - 2Q\sin^2\theta_W\big)f$$
$$- \bar{f}\gamma_\mu\gamma_5 T_3 f \big]$$
$$= J^{NV}_\mu - J^{NA}_\mu, \tag{18}$$

where Q is the charge matrix, $T_i = \sigma_i/2$ are the generators of $SU(2)$ algebra, $T^\pm = T_1 \pm i T_2$ and the vector and axial components correspond to the γ_μ and $\gamma_\mu\gamma_5$ terms, respectively. We deduce that the weak interactions would contribute a term in the Hamiltonian of the nucleon given by

$$H = \frac{4G_F}{\sqrt{2}} J^+_\mu J^{-\mu} + \frac{4G_F}{\sqrt{2}} J^N_\mu J^{N\mu} \tag{19}$$

and our objective is to calculate the difference between proton and neutron matrix elements of this operator since it gives the p–n mass splitting due to weak interactions.

It should be noted that approximating $\mathcal{L}^{\mathrm{eff}}$ in the form (16) for purely hadronic interactions presumably has large QCD corrections, which can be estimated as $\log(m_W^2/m_\rho^2) \sim 9$ assuming $m_\rho = 770$ MeV to be a typical strong interaction scale [30]. To take into account these effects, we shall introduce an enhancement factor $\mathcal{G}$ in the Hamiltonian (19). In [15] this factor has been estimated to be $\mathcal{G} \sim 7$ from current algebra considerations, and we shall use:

$$\mathcal{G} \sim 8 \tag{20}$$

as a reasonable estimate of $\mathcal{G}$.

Now, following the steps sketched in Section 2, we can develop a sum rule corresponding to the weak interactions and which is similar to Cottingham's formula. Because of weak isospin symmetry we can see that neither charged currents nor the axial part of the neutral current will contribute to the neutron–proton mass difference. Only the vector neutral current will give a non-zero contribution for the difference.

This current, however, has the same structure as the electromagnetic current and so the assumptions involved in the derivation of Cottingham's formula are still valid. Indeed, following the steps in the derivation of (8) and noting that the term $eJ_\mu^{em}A^\mu$ for the electromagnetic part of the Hamiltonian is substituted by the term $\frac{g}{\cos\theta_W}J_\mu^{NV}Z^\mu$ for the weak neutral vector part, one gets the similar result:

$$\Delta M_N^{W-NV}$$
$$= -\frac{1}{\pi}\int_0^\infty \frac{q}{M^2}dq\int_0^q d\nu\sqrt{q^2-\nu^2}\frac{4Mq^2}{q^4+4M^2\nu^2}$$
$$\times\left[3q^2 f_1^Z(q^2)-(q^2+2\nu^2)f_2^Z(q^2)\right], \qquad (21)$$

where the quantities $f_1^Z(q^2)$, $f_2^Z(q^2)$ are related to the neutral weak form factors:

$$f_1^Z(q^2)=\frac{\alpha_W}{\pi}\frac{[G_M^Z(q^2)]^2-[G_E^Z(q^2)]^2}{q^2+4M^2}, \qquad (22)$$

$$f_2^Z(q^2)=\frac{\alpha_W}{\pi}\frac{q^2[G_M^Z(q^2)]^2+4M^2[G_E^Z(q^2)]^2}{q^2(q^2+4M^2)}, \quad (23)$$

where M is the nucleon mass ≈ 1 GeV, and

$$\alpha_W=\frac{\sqrt{2}\,G_F M^2}{\pi}=0.463\times 10^{-5}. \qquad (24)$$

The sum rule (21) is the contribution to the self mass of the nucleon coming from the isospin-breaking part of the weak interaction which is, as we said above, related to the vector part of the weak neutral current. The weak contribution to the proton–neutron mass difference is obtained, then, by straightforward subtraction of the proton and neutron weak neutral vector self masses

$$\Delta M_{p-n}^W=\Delta M_p^{W-NV}-\Delta M_n^{W-NV}.$$

The weak form factors, except for isolated points, have not been measured [31]. However, using CVC, they can be related to the electromagnetic form factors [32]:

$$G^{pZ}=\frac{1}{2}(G^p-G^n)-2\sin^2\theta_W G^p-\frac{1}{2}G^{sZ}, \quad (25)$$

$$G^{nZ}=-\frac{1}{2}(G^p-G^n)-\frac{1}{2}G^{sZ}, \qquad (26)$$

where we have normalized them to the weak isospin values $G_E^{p,nZ}(0)=t_{3L}$ and where G^s is the contribu-

tion of the s-quark sea to the weak form factor. Measurements show that this latter quantity is very small and we shall neglect it [31].

The "weak Cottingham formula" (21) provides, in principle, a model independent calculation of the proton–neutron mass difference. The measured form factors neatly package many things that cannot yet be computed *ab initio*, such as the QCD structure of the nucleon. As discussed in [29], the corrections to the "weak Cottingham formula" introduced by the renormalization process should be much smaller than the rather large experimental uncertainties.

We use the "Galster parameterization" [23,24] for the electromagnetic form factors and get the final result

$$\left(\frac{M^n-M^p}{M}\right)^W=(-5.0\pm 1.0)\times 10^{-9} \qquad (27)$$

equivalent to a mass split of -4.7 ± 0.9 eV. The error was estimated from the known discrepancies of the Galster parameterization with experiment, plus a generous allowance for the largely unknown strange contribution.

4. Discussion and the Eötvös experiments

In order to see how this result can be implemented in a re-analysis of Eötvös experiments, we remind that these experiments, by measuring the difference of acceleration a for different bodies (say A, B) falling freely in a gravitational field g, set an upper limit on the difference in $\frac{\delta m}{m_I}$ for these bodies, where m_I is the inertial mass and $\delta m=m_P-m_I$ is the passive-inertial mass difference, which serves to define the Eötvös parameters $\eta(A,B)$ via

$$a_A-a_B\equiv\eta(A,B)g$$
$$=\left[\left(\frac{\delta m}{m_I}\right)_A-\left(\frac{\delta m}{m_I}\right)_B\right]g. \qquad (28)$$

Considering the mass of a nucleus with Z protons, N neutrons and binding energy B

$$m(Z,N)=ZM^p+NM^n-B \qquad (29)$$

one then introduces the violation parameters $\Gamma_{t=S,W,E}$ corresponding to different types of interactions (strong, weak and electromagnetic) through Eq. (4). As we said

earlier, the binding energy per nucleon $\bar{b} = B/(N + Z)$ is changing slowly across the periodic table and one should take into account the individual nucleons contribution to the nucleus mass in order to refine the analysis, so we get

$$\delta m = \left(\frac{N - Z}{2}\right)(\delta M^n - \delta M^p) + (N + Z)\overline{\delta M}$$
$$- \sum_{t=S,W,E} \Gamma_t E^t, \tag{30}$$

where

$$\overline{\delta M} = \frac{\delta M^p + \delta M^n}{2}$$

is the individual nucleon average passive-inertial mass difference. For simplicity, we will assume, plausibly, that the violation parameters are similar for the binding energy (3rd term) and the nucleon mass-difference (1st term) above then we have

$$\delta m = \sum_{t=S,W,E} \Gamma_t \left[\left(\frac{N - Z}{2}\right)(M^n - M^p)^t - E^t\right]$$
$$+ (N + Z)\overline{\delta M}, \tag{31}$$

where $(M^n - M^p)^t$ is the neutron–proton mass splitting due to interactions of type t. Since $\overline{\delta M}$, M^n, M^p are invariant across the periodic table one can see, considering the slow change of $\bar{b}$ and the fact that $(\frac{N-Z}{2})(M^n - M^p)$ is negligible compared to $(N + Z)(\frac{M^n + M^p}{2})$, that the last term of Eq. (31) divided by m is practically independent of the nucleus nature and can be dropped altogether from the Eötvös parameters expression, so we get

$$\eta(A, B)$$
$$= \left(\frac{\sum_{t=S,W,E} \Gamma_t[(\frac{N-Z}{2})(M^n - M^p)^t - E^t]}{m}\right)_A$$
$$- \left(\frac{\sum_{t=S,W,E} \Gamma_t[(\frac{N-Z}{2})(M^n - M^p)^t - E^t]}{m}\right)_B. \tag{32}$$

With the known expressions for E^t [13–15], the values of $(M^n - M^p)^{S,E}$ [19,20] given by Eqs. (13) and (14) (Section 2) and taking our result (Eq. (27)) for $(M^n - M^p)^W$, we could compare to the experimental $\eta(A, B)$ parameters in order to set bounds on Γ_t (see Table 1).

Table 1
Results of the Eötvös experiment

Materials	$\eta(A, B) \times 10^{11}$	Reference
Al–Au	1.0 ± 3.0	[33]
Al–Pt	0.0 ± 0.1	[34]
Cu–W	0.0 ± 4.0	[35]
Be–Al	-0.02 ± 0.28	[36]
Be–Cu	-0.19 ± 0.25	[36]
Si/Al–Cu	0.51 ± 0.67	[36]

Table 2
Upper bounds for the UFF violation parameters. The first two columns show the upper bounds obtained assuming that a single interaction breaks the equivalence principle. The first column ($\Delta M = 0$) excludes the nucleon structure contribution while the second column (ΔM_{Ct}) includes it. The last two columns show the upper bounds obtained assuming that all three interactions break the equivalence principle with the same conventions for ΔM

	$\Delta M^{n-p} = 0$	ΔM^{n-p}_{Ct}	$\Delta M^{n-p} = 0$	ΔM^{n-p}_{Ct}
Γ^S	1.0×10^{-9}	1.1×10^{-9}	1.2×10^{-8}	9.6×10^{-9}
Γ^E	1.2×10^{-9}	1.2×10^{-9}	2.8×10^{-8}	1.4×10^{-8}
Γ^W	2.8×10^{-2}	1.0×10^{-3}	4.0×10^{-1}	3.3×10^{-2}

The last two columns of Table 2 show a sample of results obtained in that way with a least squares adjustment of Eq. (32) to the data in Table 1, both excluding and including the nucleon structure contribution. We have not included the QCD enhancement factor as it is quite uncertain and because we are interested in upper bounds. We find that while the inclusion of individual nucleons effect does not change much the upper limit on the strong and electromagnetic violation parameters ($1/10^8$), it lowers the bound on Γ_W from (4×10^{-1}) to (3×10^{-2}): an order of magnitude increase in sharpness. The first two columns of Table 2 show the much sharper upper bounds obtained considering that only one of the basic interactions violates the Equivalence Principle. Again, the inclusion of nucleon structure contribution affects only slightly Γ_S and Γ_E but lowers by one order of magnitude the bound on Γ_W from 10^{-2} to 10^{-3}.

Also, if one includes the QCD enhancement factor $\mathcal{G}$ with its value from Eq. (20), one obtains, assuming that only weak interactions break the equivalence principle, the upper bound:

$$|\Gamma_W| < 2 \times 10^{-4}. \tag{33}$$

This is two orders of magnitude tighter than previously reported bounds on Γ_W [7].

As a final remark, let us observe that while proton–neutron weak mass splitting originates in the neutral currents, the "nuclear" contribution of weak interactions is dominated by the charged ones [14,15]. Thus our present results put a strong bound on both neutral and charged currents, although the present accuracy of the data and the large correlations between the Γ_t variables preclude a meaningful separation of them. The STEP experiment, with its larger accuracy and better cover of the periodic table may help to put bounds on the separate currents. However, this will depend on the exact choice of the test mass materials which, up till now, does not seem to be public. We can only expect, after the launch of STEP, an enhancement of about five or six orders of magnitude for the bounds of Table 2.

Even though we should interpret our results with caution (see Ref. [37], for examples, on mistaken analysis related to the principle of equivalence) they confirm that present Eötvös experiments do test weak interactions effect with an accuracy, at least one order of magnitude, better than previous studies.

Acknowledgements

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