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THE NEUTRON ELECTRIC DIPOLE MOMENT AS A TEST
OF THE SUPERWEAK INTERACTION THEORY

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A B S T R A C T

Theoretical calculations of the neutron electric dipole moment D_n are reviewed for various theories of CP violation. It is shown that for the superweak interaction theory D_n is less than 10^{-29} e-cm in contrast to values of 10^{-23} to 10^{-24} predicted by many but not all milliweak theories. It is concluded that prospective measurements of D_n may provide decisive evidence against or significant evidence in favour of the superweak theory.

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1. INTRODUCTION

In the ten years since the discovery of CP violation little progress has been made in determining where this violation arises in the elementary particle interactions. It follows from the assumption of CPT invariance and from a detailed analysis ¹⁾ of K^0 decay experiments even without this assumption that the CP violating interaction is also non-invariant under time reversal. As a consequence it is possible that elementary particles may have non-vanishing electric dipole moments. So far experimental searches have not revealed such moments, but it has been possible to obtain an upper limit for the electric dipole moment D_n of the neutron as low as 1.0×10^{-23} e - cm ²⁾. It now seems possible ^{3),4)} to perform much more sensitive experimental measurements of D_n . In this note we review theoretical calculations of D_n to show how the problem of CP violation can be elucidated by such measurements and, in particular, stress the importance of such measurements as a test of the superweak interaction theory.

Theories of CP violation may be divided into four general groups.

1. - Superweak interaction theory ⁵⁾

Here it is assumed that a new interaction exists which violates CP and is characterized by a coupling constant of the order 10^{-9} times the usual weak coupling G . There are two kinds of predictions that follow from the superweak theory :

Class A. All observable CP violating effects in K^0 decays may be explained in terms of a single parameter ⁶⁾ which describes the mixing of the two CP eigenstates K_1 and K_2 . Thus given one CP violating effect, such as the original observed rate of $K_L \rightarrow \pi^+ \pi^-$, all other CP violating observables are predictable. Within present accuracy such predictions have been borne out by experiment ⁷⁾.

Class B. All CP violating and T violating effects in known processes other than those in K^0 decays are extremely small, of the order 10^{-9} or less ^{*)}

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^{*)} The superweak theory allows for CP violating effects of the order 10^{-3} in $\Delta S = 2$ transition such as $\Xi \rightarrow N + \pi$, but these are so strongly forbidden that they have never been observed. If the superweak interaction is mediated by a special boson then processes involving real bosons may have large CP violation, but these bosons are so weakly coupled that their production is unlikely in the foreseeable future. Thus the limit of the order of 10^{-9} holds for "known processes"; that is, processes that have been observed or are likely to be observed in the near future.

2. - Milliweak theories *)

We call "milliweak" all theories in which CP violation is incorporated into the effective weak Hamiltonian in such a way that the consequences generally show up as a 10^{-3} correction to weak amplitudes. Many of these theories give the same class A predictions as the superweak and sometimes they are even labelled as having "superweak CP violation" ¹¹⁾ in the sense that CP violation in K^0 decays is entirely due to a single mixing parameter. However, these milliweak theories in general predict a CP violating effect in some known process at a level of 10^{-3} and so disagree with the class B predictions of the superweak theory. Unfortunately present experimental searches for CP and T violation seldom reach the level of 10^{-3} and so do not distinguish between milliweak and superweak theories.

3. - Electromagnetic CP violation

It has been suggested ¹³⁾ that the electromagnetic interaction of hadrons is intrinsically CP violating but parity conserving. Thus weak amplitudes involving hadrons (such as those of parity violating or strangeness changing processes) obtain via radiative corrections a CP violating piece of the order $\alpha/\pi \approx 10^{-3}$. An alternative hypothesis ^{14),15)}, which has similar consequences for weak amplitudes and for the neutron electric dipole moment, is that there exists an effective weak vertex for emitting photons that is CP violating and P violating and of order e times the usual weak coupling constant.

4. - Millistrong CP violation

It is even conceivable that there exists in the strong interactions an effective coupling of the order 10^{-3} that violates CP but is P invariant ^{6),16)}. This idea has not been developed in great detail; for amplitudes other than those of strong interaction processes, this theory is equivalent to a milliweak theory. For these reasons we shall not discuss this class of theories further.

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*) For a discussion of examples of older milliweak theories see Refs. 8), and 9). More recently theories of this sort have been developed ^{10),11),12)}, using the gauge formalism.

For orientation purposes we review the standard rough estimates of the electric dipole moment D_n of the neutron for the first three classes of theories ¹⁷⁾. The general approach is based on the assumption that D_n would be equal to the neutron magnetic moment or to the dimensional estimate e/M where M is the nucleon mass if it was not inhibited by the P and T selection rules. Thus in the case of electromagnetic CP violation there is no problem with T violation since we are dealing with an electromagnetic process, but we must pay with a factor G , the weak interaction coupling, for P violation. Thus we find ^{*)}

$$D_n \sim (e/M) (G/4\pi) M_x^2$$

where M_x is some characteristic mass required for dimensional reasons. In hadron physics characteristic masses are generally of the order M so that

$$D_n/e \sim (G/4\pi) M \sim 10^{-20} \text{ cm (1.E)}$$

For milliweak theories we have an effective coupling that violates P and T of order $10^{-3}G$ so that

$$D_n \sim (e/M) (G/4\pi) 10^{-3} M_x^2$$

and setting $M_x = M$

$$D_n/e \sim 10^{-3} (G/4\pi) M \sim 10^{-23} \text{ cm (1.M)}$$

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^{*)} Throughout D_n signifies the magnitude of the electric dipole moment and we do not consider the sign.

Finally for the superweak theory, assuming the superweak interaction violates P as well as CP, the factor 10^{-3} is replaced by 10^{-9} and

$$D_n / e \sim 10^{-9} (G/4\pi) M \sim 10^{-29} \text{ cm (1.s)}$$

These rough estimates are listed in the Table together with the experimental upper limit. These suggest three conclusions (1) that electromagnetic CP violation does not work (2) that present and prospective experiments are at the level to test milliweak theories, and (3) that it will be practically impossible to measure a non-vanishing D_n if the superweak theory is correct. More detailed calculations, all still very crude, are discussed in section 2 and their results are also shown in the Table. While these modify and qualify the rough estimates, they generally confirm the conclusions.

Since the proton and neutron are linked by strong interactions one expects their electric dipole moments to be of the same order of magnitude. Occasionally calculations suggest a large difference between them, but these do not involve a realistic theory of the physical nucleon and therefore should not be taken seriously. Since experiments on the neutron are far more accurate than those on the proton we shall not discuss the proton further.

Similar considerations could be made for the electric dipole moment D_e of the electron and model calculations of D_e for milliweak gauge models are included in the paper by Pais and Primack¹⁸⁾. Within each class of theories there is much more uncertainty in the estimate of D_e than there is for D_n . There are two reasons for this : (1) the mass scale may be defined either by the electron mass or by the masses of the hadrons or heavy leptons coupled to the electrons; (2) it is possible that CP violation is limited to the hadron sector in which case the electron dipole moment involves higher order weak interactions than if CP violation occurs directly for leptons. Thus the electron dipole moment provides a less clear distinction between the classes of interactions than does that of the neutron.

2. CALCULATIONS OF THE NEUTRON ELECTRIC DIPOLE MOMENT

There are two kinds of calculations of D_n . The first of these may be labelled "model independent" in the sense that for one of the three general classes of theories we are considering, the calculation is independent of any details of the model. The procedure is to consider a very limited class of intermediate states for the neutron, and to use the class of theory to determine the strength of the CP violating coupling of the neutron to those states. For the electromagnetic and milliweak cases this has been done by Barton and White ¹⁹⁾, using a sidewise dispersion relation that has proved successful in calculating the neutron anomalous magnetic moment. For the superweak interaction, we shall present a simple model independent calculation. The second kind of calculation is a detailed calculation using a specific model. Even for a given specific model it is not clear that this kind of calculation is better than the model independent one because the results are often rather ambiguous particularly since the models typically involve quarks rather than physical nucleons.

As an example of a model calculation with electromagnetic violation we show in the Table the order of magnitude of the result of Salzman and Salzman ²⁰⁾. In their model ¹⁴⁾ the intermediate boson has an intrinsic electric dipole moment so that CP violation shows up in weak electromagnetic transitions; their result agrees with the rough estimate. Many authors ^{*}), however, have made the point in various contexts that electromagnetic CP violation may be suppressed for the zero momentum photon involved in the static moment. In their model independent calculation Barton and White ¹⁹⁾ obtain a value as low as 10^{-23} cm for D_n/e if they assume some dynamical suppression at zero momentum. In case of a large suppression effects of virtual photons become important providing a term of order $(G/4\pi)e (\alpha/\pi)$, yielding as a rough estimate $D_n/e \sim 10^{-23}$ cm. We conclude then that the present experimental limit on D_n provides a significant argument against electromagnetic CP violation but does not completely rule it out.

We turn to the milliweak theories, limiting ourselves to models which are expressed in the form of renormalizable gauge theories ^{**)}.

^{*}) For example see the comments of T.D. Lee on p. 256 of Ref. 8) or similar suggestions in Ref. 21).

^{**)} Some numerical values based on older milliweak models are listed in the experimental paper of Miller et al., ²²⁾ and in Refs. 8) and 9).

While the marriage of CP violation and gauge theories appears in all cases to be a forced one, these theories have the advantage that the higher order diagrams needed to calculate D_n are in principle calculable. However, the calculated results always depend on unknown masses and strong interaction effects and so for practical purposes are no more definite than results that depend on unknown cut-offs. In spite of these drawbacks these models probably illustrate the possibilities of CP violation in the weak interactions better than earlier theories.

Pais and Primack¹⁸⁾ have calculated D_n for two milliweak models. In the first of these¹⁰⁾ CP violation appears as a relative phase factor ϕ between the V and A parts of certain strangeness changing currents; the factor ϕ is an arbitrary parameter in the theory and is given a value of 10^{-4} in order to reduce the amount of CP violation as well as to suppress other undesired effects. Pais and Primack find in this theory that the electric dipole moment D_λ of the λ quark is

$$D_\lambda \sim e G \phi m_q \sim e (m_q/M) 10^{-23} \text{ cm}$$

where M_q is a quark mass. However, they find for the non-strange quarks that the electric dipole moment vanishes in lowest order so that for the neutron quark q they find

$$D_q \sim e G \phi m_q \propto \sin \theta / \pi^3 \sim e (m_q/M) 10^{-27} \text{ cm}$$

where θ is the Cabibbo angle. In tabulating their results they use this lower value as the value of D_n , while presumably the larger value D_λ would be given as the value of D for the physical Λ particle. We consider this unreasonable, however, since the strong interactions couple the physical nucleon to a $\Lambda \bar{K}$ state; therefore, taking the strong interactions into account there is a non-vanishing contribution to D_n of order $eG\phi$ and it is not necessary to go to higher order in the weak interaction. The necessity

of going to strange particle intermediate states may give a reduction factor of the order of 10 so that we conclude ^{*)}

$$D_n / e \sim \frac{1}{10} G \phi m_e \sim 10^{-24} (m_Q / M) \text{ cm}$$

The presence of a quark mass in the answer indicates one of the problems with the calculation, but a conservative approach is to set $m_Q \sim M$ which gives the result shown in the Table.

In the other model ¹¹⁾ considered by Pais and Primack CP violation is introduced by a relative phase factor of $\pi/2$ between the couplings of the muon current to two charged intermediate bosons W_1 and W_2 . In general this phase factor has no observable consequences in the lowest order of weak interaction but can produce effects of order α/π in the next order. Thus this theory is effectively milliweak even though no small parameter of order 10^{-3} is introduced. In a purely hadronic process CP violation is typically induced by a virtual loop involving a muon and a heavy neutral lepton y_0 . In particular, the CP violation in the K^0 mass matrix is given by

$$\frac{\text{Im} (\Delta m_K)}{\text{Re} (\Delta m_K)} = 2 \times 10^{-3} = \frac{\alpha}{\pi} \left[\frac{m(y_0)}{m(W_1)} \right]^2 f_s \quad (2)$$

where f_s is some ratio of quark mass differences. Pais and Primack find for

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^{*)} Such a reduction factor of 10 is found for the contribution from strange particle intermediate states in a somewhat different context by Barton and White ¹⁹⁾.

the neutron electric dipole moment

$$\frac{D_n}{e} \sim G \frac{\alpha}{\pi^3} \left[\frac{m(\chi)}{m(W_1)} \right]^2 d^0 \quad (3)$$

where d^0 is the mass difference between two neutral charmed quarks. Combining Eqs. (2) and (3) we find

$$D_n/e \sim 2 \times 10^{-3} (G/\pi^2) (d^0/f_s) \quad (4)$$

Assuming that the combination of mass differences given by (d^0/f_s) is between 0.1 and 1.0 GeV we find $D_n/e \sim 10^{-23}$ cm.

In the theory of T.D. Lee ¹²⁾ CP violation is associated with the exchange of spin zero bosons and can be introduced as a form of spontaneous symmetry breaking using the Higgs mechanism. The smallness of the CP violation again involves the introduction of an arbitrary small parameter, although this can be related to quark mass differences. An estimate of the neutron electric dipole moment in this theory has been given by T.D. Lee ²³⁾ and is included in the Table.

We see in the Table that the various calculations for the milliweak theory all give values of the order 10^{-23} cm to 10^{-24} cm for D_n/e . In truth these "calculations" are really just slightly refined rough estimates. It is to be remembered that the calculations give explicit results in terms of unknown masses, special choices of which might give much smaller values of D_n . Furthermore these calculations give directly quark dipole moments from which it is necessary to estimate the physical nucleon dipole moment. The model independent calculation of Barton and White has the advantage of treating the nucleon more realistically. In their calculation the milliweak CP violation is introduced through the assumption that the P violating CP violating nucleon nucleon pion (NN π) vertex is 10^{-3} times the usual

(CP invariant) weak P violating $NN\pi$ vertex. Since the usual weak vertex is proportional to $\sin^2\theta$ as a result of CP invariance²⁴⁾, they obtain a result proportional to $\sin^2\theta$ and of the order 10^{-24} cm. However, we consider this $\sin^2\theta$ suppression unreasonable for the CP violating vertex (and it does not occur in the models discussed above) since it entered in the first place as a result of CP invariance and so we quote their result as 10^{-23} cm.

In spite of the agreement among these calculations of D_n for milliweak theories it must be emphasized that it remains easy to construct milliweak theories in which D_n is suppressed by an extra factor as large as 10^5 or 10^6 . All that is required is that the CP violating part of the effective weak Hamiltonian satisfies a selection rule that prevents it from contributing to the electric dipole moment of any hadron. One example is that of theories in which all CP violating terms in the Hamiltonian have $|\Delta S| = 1$ ⁹⁾. It is then necessary to go to the next order in the weak interaction to obtain another term with $|\Delta S| = 1$ in order that the effective operator connects states of the same strangeness. Thus the rough estimate of D_n in such theories is

$$D_n \sim (e/M) 10^{-3} (G/4\pi)^2 M_x^4$$

The choice of M_x^4 depends on the way on which higher order weak interaction effects are made convergent, but if we set $M_x \approx M$ as we did before

$$D_n/e \sim 10^{-3} (G/4\pi)^2 M^3 \sim 10^{-29} \text{ cm} \quad (5)$$

as in the superweak theory. Recently a gauge model with this feature has been proposed²⁵⁾ by Frenkel and Ebel; they estimate

$$D_n/e \sim \sin(\Delta\alpha) \times 10^{-26} \text{ cm.}$$

where $\Delta\alpha$ is the CP violating phase introduced in the model. If we set

$\Delta\alpha = 10^{-3}$ so that the CP violation is milliweak ^{*)}, we find $D_n/e \simeq 10^{-29}$ cm in agreement with the estimate of Eq. (5).

Another example is that of theories in which all CP violating terms are parity conserving ²⁶⁾. It is again necessary to go to the next order in the weak interaction to produce the parity violation required for a non-zero electric dipole moment. Thus the estimate of Eq. (5) would again be expected to hold. Such models have the added feature of exactly reproducing the class A predictions of the superweak theory. We do not know of a gauge theory of this type, but the demonstrated dexterity of professional gauge theory modelists suggests that they can construct such a model if it be needed.

For the case of the superweak interaction, we know of no published calculations of D_n . The basic idea of the superweak interaction is that the CP violating interaction can be very weak because it contains a $\Delta S = 2$ part that causes a mixing of K^0 and $\bar{K}^0$ (or K_1 and K_2) in lowest order. The strength of the superweak interaction H_{sw} is empirically defined by the assumption that the matrix element producing the mixing between K_1 and K_2 is uninhibited and representative. The magnitude of the observed CP violation determines

$$\langle K_1 | H_{sw} | K_2 \rangle \approx 3 \times 10^{-3} (m_L - m_S) \approx 2 \times 10^{-17} m_K \quad (6)$$

where M_L, M_S, M_K are the masses of K_L, K_S , and K , respectively.

To estimate the magnitude of D_n we use a simple non-relativistic perturbation formula

$$D_n = \sum_m \frac{\langle n | H_{sw} | m \rangle \langle m | \partial | n \rangle + \langle n | \partial | m \rangle \langle m | H_{sw} | n \rangle}{E_m - E_n} \quad (7)$$

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*) Frenkel and Ebel discuss the possibility that $\Delta\alpha$ could be of the order of unity for a special choice of their parameters. This choice would seem to be ruled out by the failure to observe large T violations in Δ decays.

where n is the neutron state, $\mathcal{D}$ is the electric dipole moment operator, and m are intermediate states, essentially excited spin $-\frac{1}{2}$ states of opposite parity from the nucleon. The T violating property of H_{sw} is required so that the sum does not vanish. We approximate the sum by replacing m by a single state (or group of states) n^* . We may use dimensional arguments to estimate

$$\langle n^* | \mathcal{D} | n \rangle = e/M \quad (8)$$

Alternatively we may use the sum rule that relates $\sum_n |\langle m | \mathcal{D} | n \rangle|^2$ to the mean square radius of the neutron; since the latter is experimentally consistent with zero, the value given in Eq. (8) is not unreasonably small. The same result is obtained if n^* is identified as the $1550 S_{11}$ state¹⁹⁾. In our calculation the superweak interaction serves once again to mix single particle states; in this case the neutron state with the excited state n^* of opposite parity. If we assume this mixing is not inhibited, as we assumed before in the case of $K_1 - K_2$ mixing, then it is reasonable that

$$\langle n^* | H_{sw} | n \rangle \approx \langle K_2 | H_{sw} | K_1 \rangle \approx 2 \times 10^{-17} m_K \quad (9)$$

Combining Eqs. (7), (8), and (9) we have

$$D_n \approx 4 \times 10^{-17} (e/M) (m_K / (E_{n^*} - E_n))$$

Assuming $E_{n^*} - E_n \approx m_K$

$$D_n / e \sim 4 \times 10^{-17} / M \sim 10^{-30} \text{ cm.} \quad (10)$$

Allowing for a factor of 10 uncertainty we may interpret this result as giving an upper limit for D_n in the superweak theory

$$D_n / e < 10^{-29} \text{ cm} \quad (11)$$

As a prediction of the superweak theory our result Eq. (10) depends most critically on the assumption that the matrix element of Eq. (9) does not vanish as a result of selection rules. In order that the matrix element in Eq. (6) be uninhibited it is required that a sizeable part of H_{sw} be parity conserving and allow $\Delta S = 2$. In order that the matrix element of Eq. (9) be uninhibited it is required that a sizeable part of H_{sw} satisfy the quite different requirements of being parity violating and allowing $\Delta S = 0$. The superweak interaction theory is really a class of theories and it is easy to construct specific models in which this last condition is or is not satisfied. If it is not satisfied; that is, H_{sw} is either parity conserving or requires $\Delta S \neq 0$, then the superweak prediction for D_n would be 10^5 to 10^6 times lower than given by Eq. (10). We have already noted this same problem for milliweak theories as a class.

The inequality Eq. (11) is the most definite prediction of the superweak theory independent of further specifications of the theory. The approximation of a single intermediate state in Eq. (7) does not seem critical since if higher states are included their values of $\langle m | \mathcal{O} | n \rangle$ must be appropriately smaller to satisfy the sum rule previously mentioned. Thus our major assumption is that of Eq. (9); however, a much larger value for $\langle n^* | H_{sw} | n \rangle$ would be contrary to the basic assumption of the superweak theory that the matrix element $\langle K_2 | H_{sw} | K_1 \rangle$ is not inhibited.

The form of Eq. (7) implies that H_{sw} has no structure, such as that due to an intermediate boson, since if it does there could be contributions to D_n in which the photon comes from the structure. Indeed, in calculations of D_n in milliweak models, an important contribution sometimes comes from the current of the intermediate boson. Thus we offer a more general, though less detailed, derivation of our result. In calculating D_n in relativistic perturbation theory one draws all "self-energy graphs" that involve H_{sw} to lowest order and then appends the external photon line consecutively in all possible places. This is similar in principle to the calculation of the anomalous magnetic moment μ_a , in which H_{sw} is replaced by the strong interaction. Thus we expect

$$D_n / \mu_a \sim (\Delta m)_{sw} / (\Delta m)_{strong}$$

where $(\Delta m)_{sw}$ is the superweak self energy and $(\Delta m)_{strong}$ is a strong self-energy. From our previous discussion

$$(\Delta m)_{sw} \approx 2 \times 10^{-17} m_K$$

setting $(\Delta m)_{strong} \sim m_\pi$ we have

$$D_n / e \sim 2 \times 10^{-17} (m_K / m_\pi) (u_2 / e) \sim 10^{-30} \text{ cm}$$

which is essentially the same as the previous result.

One might ask why this general argument cannot be used in the case of milliweak theories, particularly those with "superweak CP violation". The reason is that in these theories, the CP violating K^0 self-energy, or mixing term does not appear in lowest order because of the selection rule $\Delta S = 0, 1$, so that the CP violating neutron electric dipole moment, which involves $\Delta S = 0$, can appear in a lower order. Thus there is no simple relation between the CP violation in the K^0 system and that which produces D_n . In contrast the basic assumption of the superweak theory is that $\Delta S = 2$ occurs in lowest order.

3. CONCLUSION

The present experimental limit on D_n provides significant but not decisive evidence against electromagnetic CP violation. If further experiments lower this limit by an order of magnitude it would seem reasonable to rule out electromagnetic CP violation although models with special features might be found to fit within this limit.

For most of the milliweak theories considered here the calculations, admittedly very rough, give values of D_n / e between 10^{-23} and 10^{-24} cm .

It is therefore likely, if the milliweak explanation is correct, that future experiments should find a non-vanishing value of D_n/e as they explore values between 10^{-23} cm, the present limit, and 10^{-26} cm. Such a non-vanishing value would decisively demonstrate that the superweak theory is incorrect, since we have argued that, independent of details, this theory must yield a value less than 10^{-29} cm. A discovery of such a non-vanishing value would provide a powerful impetus for searches for other CP violating effects predicted by milliweak theories.

If the electric dipole moment of the neutron continues to be consistent with zero as values of D_n/e are searched in the range 10^{-26} to 10^{-28} cm⁴⁾, this would provide significant evidence in favour of the superweak theory. However, as we have emphasized, this would not be decisive because it is possible to devise milliweak theories with selection rules that could depress the value of D_n/e to 10^{-29} cm. Nevertheless more precise measurements of the neutron electric dipole moment seem to be the best test of a class B prediction of the superweak theory that is likely to be done in the near future. No experiment proposed using accelerators in the range of 10^9 to 10^{12} eV seems nearly so sensitive as the measurement of D_n using neutrons of 10^{-3} eV.

T A B L E

	Values of D_n/e in cm for various theories		
	Electromagnetic	Milliweak	Superweak
Rough estimate	10^{-20}	10^{-23}	10^{-29}
Model independent calcul.	10^{-21} to 10^{-23}	10^{-23}	10^{-30}
Salzman and Salzman	10^{-20}	-	-
T.D. Lee	-	10^{-23}	-
Mohapatra	-	10^{-24}	-
Pais	-	10^{-23}	-
Frenkel and Ebel	-	10^{-29}	-
Experimental result	$\leq 10^{-23}$		

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