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► **To cite this version:**

| Jean-Marcel Rax. Zitterbewegung CPT Violation in a Neutral Kaons System. 2024. hal-04501229

HAL Id: hal-04501229

<https://hal.science/hal-04501229>

Preprint submitted on 12 Mar 2024

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Zitterbewegung CPT Violation in a Neutral Kaons System

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(Dated: March 12, 2024)

The observed CP violation in neutral kaons experiments is explained as an interplay between two oscillations in the earth's Schwarzschild geometry: (i) mixing associated with second order weak coupling and (ii) strange quark's zitterbewegung. This violation is in fact a CPT violation with T conservation rather than a T violation with CPT conservation. The Hermitian evolution of a stable kaons system leads to the identification of this CPT violation. Then, the finite lifetime of the short-lived kaon rotates the violation parameter such that it appears as a T violation.

Sixty years ago J. Christenson, J. Cronin, V. Fitch and R. Turlay reported the first measurement of CP violation [1–3]. Following decades of precision measurements this small CP asymmetry is now incorporated in the Standard Model.

The Lee, Oehme and Yang (LOY) model [4, 5], based on two coupled Schrödinger equations, provides the canonical framework to describe the dynamics of neutral kaons. In this letter we revisit the influence of the earth gravitational field on neutral kaons dynamics [6–9] and extend the LOY model to account for this influence.

We demonstrate that earth induces a CPT violation with a T conservation, fully consistent with the experimental results and usually interpreted as a CP violation with T violation and CPT conservation.

First, assuming that the long-lived kaon K_L and the short-lived one K_S are stable particles, we find that the overlap of CP eigenstates $\langle K_S | K_L \rangle$ is an imaginary number (T conservation and CPT violation).

Then, taking into account the finite lifetime of K_S , the observed $\langle K_S | K_L \rangle$ is rotated and becomes a real number (apparent T violation) with the value given by the experimental data. The measurement of $\langle K_S | K_L \rangle$ providing this real value favored, in the past, the inclusion of this gravitational effect as a CP and T violations in the LOY model, rather than CPT violation with T conservation.

The details of the demonstration, the consequences of the results, and some perspectives, can be found in a longer companion paper [10]. The origin of direct CP violation finds also its interpretation with this new mechanism and the derivation of the parameter ε' is presented in the longer companion paper [10], this letter is restricted to ε . We set $\hbar = c = 1$. Most of the references are not recent because the subject of earth as the origin of CP violation did not attract much interest during the past decades.

We follow the way Dirac resolved the apparent contradiction between the requirements of relativistic dynamics and quantum mechanics: (i) energy-momentum dispersion relations are quadratic forms, however (ii) wave

equations are linear forms with respect to energy/time derivation in order to define a positive probability density [11]. Dirac developed a first order quantum evolution such that the iteration of the time derivation yielded the relativistic quadratic dispersion relation, in doing so he identified the γ matrices algebra.

In this letter, we use the iteration of the LOY first order wave equations to set up coupled Klein-Gordon equations revealing the principal gravitational coupling to be considered in the first order wave equations.

The main results of this letter are: (i) the origin of indirect CP violation in kaons systems is identified, (ii) the measured value of the indirect CP violation parameter is predicted and (iii) the right status of the symmetry violation induced by curvature and quarks zitterbewegung is restored: CPT violation with T conservation rather than T violation with CPT conservation. T violation appears as a result of the K_L decays described as an irreversible process with the Weisskopf-Wigner approximation [12].

The rest frame evolution of a neutral kaons system (K^0/\bar{K}^0) is described by two amplitudes defining the state $|\Psi\rangle$ as a function of the particle proper time τ ,

$$|\Psi\rangle = a(\tau) |K^0\rangle + b(\tau) |\bar{K}^0\rangle. \quad (1)$$

The two CP and energy eigenstates, $|K_1\rangle$ and $|K_2\rangle$ are the normalized sum and difference of $|K^0\rangle$ and $|\bar{K}^0\rangle$. The Weisskopf-Wigner approximation [12] describes decay through a nonhermitian Hamiltonian H_K driving a first order proper time evolution $H_K |\Psi\rangle = j\hbar\partial_\tau |\Psi\rangle$ with

$$H_K = Mc^2 \left(|K^0\rangle \langle K^0| + |\bar{K}^0\rangle \langle \bar{K}^0| \right) - \delta Mc^2 \left(|\bar{K}^0\rangle \langle K^0| + |K^0\rangle \langle \bar{K}^0| \right). \quad (2)$$

This Hamiltonian looks like relativistic because of the occurrence of c , but in fact it provides a description which is not fully relativistic. The matrix elements $M = m - j\hbar\Gamma/2c^2$ and $\delta M = \delta m - j\hbar\delta\Gamma/2c^2$ can be found in [13] and in the companion paper [10].

In the following we restrict H_K to its Hermitian part ($\Gamma = -\delta\Gamma = 0$) to avoid unphysical *interferences* between (i) phenomenological Weisskopf-Wigner damping ($\Gamma, \delta\Gamma$)

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and (ii) first principles from quantum mechanics and general relativity. The interplay between Weisskopf-Wigner decay and first principles is the source of a confusion between CPT and T violations. In a flat spacetime the Hermitian evolution ($\Gamma = -\delta\Gamma = 0$) of (1) is

$$j \frac{\partial}{\partial \tau} \begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} m & -\delta m \\ -\delta m & m \end{bmatrix} \cdot \begin{bmatrix} a \\ b \end{bmatrix}. \quad (3)$$

The relativistic energy (E)-momentum (p) relation is: $E^2 - p^2 = m^2$. To set up a quantum description ($E \leftrightarrow j\partial/\partial\tau$) we have to consider the particle rest frame ($p = 0$) relation $\langle K^0 | E | K^0 \rangle = \pm m$. The relations used in Eq. (3) are the rest frame restrictions ($p = 0$) of the operator $+\sqrt{p^2 + m^2}$ which is non-local in a flat spacetime and can not operate in a curved spacetime. A local evolution $E^2 = p^2 + m^2$ is more appropriate to work in a curved spacetime.

An other critics of Eq. (3) is that nothing indicates that \bar{K}^0 is the antiparticle of K^0 . These are two particles with the same mass. This drawback is cured with the Feynman prescription: if two additional velocity matrix elements are to be considered, we must allocate a positive and a negative sign in order to describe one (the particle) propagation forward in time and one (the antiparticle) propagation backward.

The earth Schwarzschild radius is $R_S = 2GM_\oplus/c^2 = 8.87 \times 10^{-3}$ m where M_\oplus is the earth mass and G the gravitational constant. The earth radius R_\oplus is far larger than $R_S \sim 10^{-9}R_\oplus$. In a Schwarzschild spacetime, with time t and radial coordinate r , the energy E of a particle, with proper time τ at a distance r from the origin, is no longer $E = mdt/d\tau$ and is given by:

$$E = m(1 - R_S/r) dt/d\tau. \quad (4)$$

The radial position r is the instantaneous *barycentric* position of the mass/energy associated with the down d/\bar{d} and strange s/\bar{s} quarks dynamics inside the kaons. These quarks perform an unknown, small scale, high frequency motion with respect to an average center of mass/energy. This average center of mass/energy of the kaon follows a geodesic: a very slow vertical free fall combined with a fast (almost) horizontal inertial motion. Moving to the horizontal inertial frame of the kaon, the radial position r is decomposed as $r = R_\oplus + X + x$ the sum of: (i) the earth radius R_\oplus , plus (ii) the average vertical displacement $X(\tau)$, with respect to R_\oplus , which is the average classical slow free fall motion of the kaon (τ is the proper time of the kaon), plus (iii) the fast, unknown, internal vertical motion x , with respect to $R_\oplus + X$, of the instantaneous *barycentric* position of the mass/energy associated with the quarks zitterbewegung dynamics. The ordering $X + x \ll R_\oplus$ allows to expand the energy (4) in the kaon frame where $t = \tau$:

$$E = m \left[1 - (R_S/R_\oplus) + (R_S/R_\oplus^2)(X + x) \right]. \quad (5)$$

The proper time τ is the kaon rest frame time along a geodesic and $X(\tau)$ is the vertical part of this geodesic, so it can not operate on the kaon internal state: in the kaon rest frame X is an additional time dependant energy. The case is different for the quarks vertical motions x around $R_\oplus + X$ because τ is not the proper time of the quarks. The internal position operator \hat{x} operate in the tensorial product space of d and s Dirac's spinors states. Kaons are spin 0 diquark. We note: $|K^0\rangle = |d\bar{s}\rangle$ and $|\bar{K}^0\rangle = |\bar{d}s\rangle$. In the kaons Hilbert space ($|K^0\rangle, |\bar{K}^0\rangle$) \hat{x} is given by:

$$\hat{x} = \langle d\bar{s} | \hat{x} | d\bar{s} \rangle |K^0\rangle \langle K^0| + \langle \bar{d}s | \hat{x} | \bar{d}s \rangle |\bar{K}^0\rangle \langle \bar{K}^0| + \langle d\bar{s} | \hat{x} | \bar{d}s \rangle |K^0\rangle \langle \bar{K}^0| + \langle \bar{d}s | \hat{x} | d\bar{s} \rangle |\bar{K}^0\rangle \langle K^0|. \quad (6)$$

The dimension of the tensorial product of diquark spinor space $|qq\rangle$ is 16. The mass of the s/\bar{s} strange component account for 96% of the sum of the d/\bar{d} and s/\bar{s} components, thus we can neglect the dynamics of the d/\bar{d} quark. The s and \bar{s} carry internal kinetic and potential energy in addition to mass energy and this internal en-

ergy is attached to the strange quark motion, the lighter quarks d and \bar{d} are just followers of the kaons slow free fall dynamics and passive witness of the s/\bar{s} fast zitterbewegung motion. The Schrödinger LOY equation on earth with $R_S \neq 0$ and $\Gamma = -\delta\Gamma = 0$ is:

$$j \frac{\partial |\Psi\rangle}{\partial \tau} = m |\Psi\rangle - \delta m \left[|\bar{K}^0\rangle \langle K^0| + |K^0\rangle \langle \bar{K}^0| \right] |\Psi\rangle - m \frac{R_S}{R_\oplus^2} [R_\oplus - X(\tau)] |\Psi\rangle + m \frac{R_S}{R_\oplus^2} \hat{x} \cdot |\Psi\rangle. \quad (7)$$

The first and third terms on the right hand side of Eq. (7) are easily eliminated to obtain a more simple repre-

sentation of the kaons state

$$|\Phi\rangle = |\Psi\rangle \exp jm \left[\tau - \frac{R_S}{R_\oplus} \left(\int_0^\tau du - \int_0^\tau \frac{X(u)}{R_\oplus} du \right) \right]. \quad (8)$$

As $R_S/R_\oplus \sim 10^{-9}$ and $R_S X/R_\oplus^2 \sim X [\text{m}] \times 10^{-16}$ both gravitational terms in (8) are negligible compared to $m\tau$ and unobservable with interferometric experiments (they add up in the same way to the mass of K_S and K_L). We can safely neglect the R_S/R_\oplus term in (8) and define the amplitudes u and v of Φ ,

$$|\Phi\rangle = |\Psi\rangle \exp jm\tau = u(\tau) |K^0\rangle + v(\tau) |\bar{K}^0\rangle. \quad (9)$$

Under the assumption of the strange quark dynamical dominance u and v fulfill

$$j \frac{\partial}{\partial \tau} \begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} 0 & -\delta m \\ -\delta m & 0 \end{bmatrix} \cdot \begin{bmatrix} u \\ v \end{bmatrix} + m \frac{R_S}{R_\oplus^2} \times \begin{bmatrix} \langle \bar{s} | \hat{x} | \bar{s} \rangle & \langle \bar{s} | \hat{x} | s \rangle \\ \langle s | \hat{x} | \bar{s} \rangle & \langle s | \hat{x} | s \rangle \end{bmatrix} \cdot \begin{bmatrix} u \\ v \end{bmatrix}. \quad (10)$$

where we have used Eqs. (6,7,8,9). The Compton wavelength ($\lambda_C = \hbar/mc = 3.9 \times 10^{-16}$ m) of the kaon provides an upper bound of $\langle \hat{x} \rangle$ in (10) as quarks are bound states inside the volume of the kaon. The value $R_S \lambda_C / R_\oplus^2 \sim 8.6 \times 10^{-32}$ leads to the occurrence of a very strong ordering fulfilled by these four matrix elements in front of $\delta m/m \sim 3.5 \times 10^{-15}$.

Following Dirac's historical method, the fully relativistic dynamics associated with (10) is explored through an iteration of the time derivation. Among the various gravitational terms we keep only the dominant one, the others ($m^2 R_S^2 \lambda_C^2 / R_\oplus^4 \delta m^2 \sim 10^{-34}$ and $m R_S \lambda_C / \delta m R_\oplus^2 \sim 10^{-17}$) are negligible,

$$-\frac{\partial^2}{\partial \tau^2} \begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} \delta m^2 & 0 \\ 0 & \delta m^2 \end{bmatrix} \cdot \begin{bmatrix} u \\ v \end{bmatrix} + jm \frac{R_S}{R_\oplus^2} \times \begin{bmatrix} \frac{\partial}{\partial \tau} \langle \bar{s} | \hat{x} | \bar{s} \rangle & \frac{\partial}{\partial \tau} \langle \bar{s} | \hat{x} | s \rangle \\ \frac{\partial}{\partial \tau} \langle s | \hat{x} | \bar{s} \rangle & \frac{\partial}{\partial \tau} \langle s | \hat{x} | s \rangle \end{bmatrix} \cdot \begin{bmatrix} u \\ v \end{bmatrix} \quad (11)$$

A straightforward calculation with Dirac's equation describing s/\bar{s} quarks bounded in a kaon (presented and developed in the longer companion paper [10]) demonstrates that

$$\frac{\partial}{\partial \tau} \begin{bmatrix} \langle \bar{s} | \hat{x} | \bar{s} \rangle & \langle \bar{s} | \hat{x} | s \rangle \\ \langle s | \hat{x} | \bar{s} \rangle & \langle s | \hat{x} | s \rangle \end{bmatrix} = \begin{bmatrix} 0 & c \\ c & 0 \end{bmatrix}. \quad (12)$$

This result belongs to the set of effects called *zitterbewegung* [11]: the Dirac position operator \hat{x} operating on spin 1/2 fermions spinors displays unfamiliar and non-intuitive properties, the associated velocity operator (involved in the left hand side matrix in (12)) has two eigenvalues $\pm c$ associated with four eigenvectors describing pairs of fermion/antifermions [11]. These velocity operator properties give (12). This *zitterbewegung* behavior is the origin of the value of the non diagonal elements in (12). The diagonal elements are zero because the average quark velocity in a bound state is zero [10].

We define the parameter κ :

$$\kappa = \frac{m\hbar}{\delta m^2 c} \frac{R_S}{4R_\oplus^2} = \left(\frac{m}{2\delta m} \right)^2 \frac{R_S \lambda_C}{R_\oplus^2} = 1.7 \times 10^{-3}, \quad (13)$$

With the *zitterbewegung* property (12), equation (11) is then reduced to a simple square with an accuracy $O[\kappa^3] \sim 10^{-9}$

$$-\frac{\partial^2}{\partial \tau^2} \begin{bmatrix} u \\ v \end{bmatrix} = \left(\pm \begin{bmatrix} 0 & \delta m \\ \delta m & 0 \end{bmatrix} \pm \delta m \begin{bmatrix} 2j\kappa & 2\kappa^2 \\ 2\kappa^2 & 2j\kappa \end{bmatrix} \right)^2 \cdot \begin{bmatrix} u \\ v \end{bmatrix} + \delta m^2 \times O \begin{bmatrix} \kappa^4 & \kappa^3 \\ \kappa^3 & \kappa^4 \end{bmatrix} \cdot \begin{bmatrix} u \\ v \end{bmatrix}. \quad (14)$$

Despite the fact that this rest frame Klein-Gordon evolution is associated with a local and complete relativistic dispersion, the right framework to describe a quantum evolution is a set of first order equations. The solutions of the second-order equation (14) includes redundant solutions which do not satisfy (10). Among the first order equations leading to (14) we have to consider one whose limit is (3) when $\kappa = 0$.

From (14) we go back to (u, v) first order evolutions and then to the initial kaons amplitudes (a, b) with the help of the change of variables from (9) to (1),

$$j \frac{\partial}{\partial \tau} \begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} m & -\delta m \\ -\delta m & m \end{bmatrix} \cdot \begin{bmatrix} a \\ b \end{bmatrix} + \delta m \begin{bmatrix} 2j\kappa & -2\kappa^2 \\ -2\kappa^2 & -2j\kappa \end{bmatrix} \cdot \begin{bmatrix} a \\ b \end{bmatrix}. \quad (15)$$

As $\kappa \sim \partial \langle \bar{s} | \hat{x} | s \rangle / \partial \tau$ is proportional to a velocity matrix

element, to distinguish the K^0 from the \bar{K}^0 , we have implemented Feynman's prescriptions in going from (14) to (15) so that a describe the amplitude of a particle whose antiparticle is described by b . Moreover this ensures that the energy eigenvalues are real. These energy eigenvalues of (15) are: $m \mp \delta m$ with an accuracy $\delta m \times 10^{-12}$.

The eigenvectors ($O[\kappa^2]$ terms are neglected) associated with the time evolutions $\exp -j(m \pm \delta m)\tau/\hbar$ are

$$|K_{L/S}^\oplus\rangle = \frac{1 \pm j\kappa}{\sqrt{2}} |K^0\rangle \mp \frac{1 \mp j\kappa}{\sqrt{2}} |\bar{K}^0\rangle, \quad (16)$$

(L and S are respectively associated with the upper and lower sign). A better accuracy, neglecting $O[\kappa^3]$, can be easily achieved [10] but it does not change the results below. The very first consequence of (16) is the identification of the origin of CP violation and its characterization

as a *CPT* violation with *T* conservation

$$\langle K_S^\oplus | K_L^\oplus \rangle \Big|_{\Gamma = -\delta\Gamma = 0} = 2j\kappa. \quad (17)$$

The two stable kaons $|\tilde{K}_L\rangle$ and $|\tilde{K}_S\rangle$ solution of Eq. (15) evolve in time according to

$$|\tilde{K}_{L/S}\rangle = \exp -j(m \pm \delta m)\tau |K_{L/S}^\oplus\rangle. \quad (18)$$

Then, to work within the framework of the experimental conditions, we take into account the K_S decays. We assume that K_L is stable, and not depleted by K_S gravitational regeneration, and that K_S is unstable. In the following a star index ($*$) indicates the *dressing* resulting from the opening of the K_S decay channels of the *bare* stable state $|\tilde{K}_S\rangle$. The *dressed* kaons energy eigenstates, $|K_{L*}^\oplus\rangle$ and $|K_{S*}^\oplus\rangle$, are defined through relations similar to (18)

$$|\tilde{K}_{L*/S*}\rangle = \exp -j(m \pm \delta m)\tau |K_{L*/S*}^\oplus\rangle. \quad (19)$$

Within the framework of the Weisskopf-Wigner approximation the evolution of \tilde{K}_{S*} is described by: (*i*) a decay with a rate $(\Gamma - \delta\Gamma)/2 \approx \Gamma \approx -\delta\Gamma$ and (*ii*) a gravitational regeneration with a rate $|\tilde{K}_L\rangle \partial \langle \tilde{K}_L | \tilde{K}_S \rangle / \partial \tau$ and (18) gives

$$\frac{\partial}{\partial \tau} \langle \tilde{K}_L | \tilde{K}_S \rangle = 2j\delta m \langle K_L^\oplus | K_S^\oplus \rangle \exp 2j\delta m\tau. \quad (20)$$

The Schrödinger equations for the dressed K_{S*} is a balance between decay and gravitational regeneration from a steady state K_{L*} amplitude,

$$\begin{aligned} \frac{\partial |\tilde{K}_{S*}\rangle}{\partial \tau} &= -j(m - \delta m) |\tilde{K}_{S*}\rangle - \Gamma |\tilde{K}_{S*}\rangle \\ &+ |\tilde{K}_{L*}\rangle \left(\frac{\partial}{\partial \tau} \langle \tilde{K}_L | \tilde{K}_S \rangle \right). \end{aligned} \quad (21)$$

The observed experimental *CP* violation parameter $\langle K_{L*}^\oplus | K_{S*}^\oplus \rangle$ is obtained as the balance between the last two terms on the right hand side of (21)

$$-\Gamma \langle K_{L*}^\oplus | K_{S*}^\oplus \rangle + 2j\delta m \langle K_L^\oplus | K_S^\oplus \rangle = 0, \quad (22)$$

where we have used (20), (19) and $\langle K_{L*}^\oplus | K_{L*}^\oplus \rangle = 1$. Despite the fact that the *bare* parameter $\langle K_L^\oplus | K_S^\oplus \rangle$ is an imaginary number, the measured *CP* violation parameter $\langle K_{L*}^\oplus | K_{S*}^\oplus \rangle$ is a real number because of K_S finite lifetime,

$$\left. \frac{\langle K_{L*}^\oplus | K_{S*}^\oplus \rangle}{2} \right|_{\Gamma = -\delta\Gamma \neq 0} = \kappa \frac{2\delta mc^2}{\hbar\Gamma} = 1.6 \times 10^{-3}, \quad (23)$$

in good agreement with the experimental $\text{Re}(\varepsilon)$ [14]. Note that, if the restriction of the dynamics to the

strange quark is taken into account through a lowering of the mass m to $(m_s/m_d + m_s) \times m$, this gives 1.60×10^{-3} .

The numerical coincidence $mgh/(2\delta m)^2 c^3 \approx \text{Re} \varepsilon/2$ ($g = c^2 R_S/2R_\oplus^2 = 9.8 \text{ m/s}^2$) was identified four decades ago by E. Fischbach [15]. Fischbach was exploring the impact of gravitation and he noted the puzzling relation: a simple *ad hoc* increase by a factor $m/2\delta m$ of the coupling $\hbar g/2\delta mc^3$ gives $\text{Re} \varepsilon/2$.

At the fundamental level the *CP* violation observed on earth in the K_L/K_S system is a *CPT* violation and the K_S finite lifetime makes it appear as a *T* violation.

Finally the K_L instability can also be taken into account with the Bell-Steinberger unitarity relations [16]. The result is $\arg(\varepsilon) \approx 43, 4^\circ$ [10] in good agreement with the experimental data [14]. The origin of direct violation finds also an explanation within the framework of this new mechanism. We report here the results obtained in the companion paper [10]: if the parameters are expressed in a phase convention independent format then the ratio $\text{Re}(\varepsilon'/\varepsilon)$ is 1.6×10^{-3} .

The simplicity of the mechanism and the agreement between the predicted values of the *CP* violation parameters and the experimental data allow to conclude that the set of relations Eqs. (15,16,21,23) is an operational framework to explain *CP* violations in kaons experiments on earth, provided that: (*i*) the dissipative dressing of the various amplitude and (*ii*) their dependence/independence on initial phase conventions are carefully taken into account.

This new mechanism of *CP* violation results from the interplay between two oscillations: (*i*) quarks's zitterbewegung inherent to fermion/antifermion pairs and (*ii*) kaons mixing associated with second order weak interaction coupling. As the frequencies of these two oscillations are rather different, this is a secular effects like the ponderomotive shift/force [17] which is usually described in term of an *effective* mass in analytical mechanics [18].

This mechanism of *zitterbewegung CP violation* might change the way we understand how our matter-dominated universe emerged during its early evolution. The observed present level of *CP* violation on earth is at least ten orders of magnitudes smaller than the one needed to explain the observed matter-antimatter asymmetry. At a distance R from the center of a massive object, or a large energy fluctuation, with Schwarzschild radius R_S , the amplitude of the *CP* violation parameter (23) is the product of three factors: $(m/2\delta m)^2$ and $(2\delta mc^2/\hbar\Gamma)$ which are associated with the fundamental interactions (electromagnetic, weak and strong), and $(R_S \lambda_C/R^2)$ which is associated with spacetime and can be far larger than its earth value. Larger perspectives are presented in the longer companion paper [10].

ACKNOWLEDGMENTS

This work was undertaken during a sabbatical year at Princeton and completed at the University of Paris-Saclay. The financial support of a G. R. Andlinger fellowship from Princeton University ACEE is acknowledged. The author gratefully thanks Prof. N. Fisch and his

team, Drs. E.J. Kolmes, M.E. Mlodik, I.E. Ochs and T. Rubin, for their warm welcome in their aneutronic fusion project and for the intellectual atmosphere which provided him the ideal conditions for simultaneously addressing the issues of aneutronic fusion and this long-standing CP problem.

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