

A QUEST FOR NEW PHYSICS INSIDE THE NEUTRON*

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The lecture presents an overview of the quest for the new physics in low energy neutron phenomena. In addition to the traditional topics the quantum damping of $n\bar{n}$ oscillations is discussed.

I. INTRODUCTION

The lecture has been delivered for young physicists and students with only basic knowledge of neutron physics. There are obvious caveats for experts associated with this. For the same reason the list of references is in no way intended to be complete.

Neutron was discovered by James Chadwick – in 1932. Its main characteristics – mass, lifetime, magnetic moment, may be found in Particle Data Group (PDG) Reviews. It might seem strange, but neutron lifetime is still a controversial subject. This will be the topic of the next section. Probably the main breakthrough in the new physics associated with neutron is the discovery of parity nonconservation observed in 1956 by Chien-Shiung Wu group following the theoretical physicists Tsung-Dao Lee and Chen-Ning Yang idea. The experiment monitored the β decay of ^{60}Co ($^{60}\text{Co} \rightarrow ^{60}\text{Ni} + e^- + \bar{\nu}_e$, or $d \rightarrow u + e^- + \bar{\nu}_e$ at the quark level). The ^{60}Co nuclei were aligned along the direction of an external magnetic field. The decay probability may be written as

$$W = W_0 \left[1 + a_{Sp}(\vec{S}_N \vec{p}_e) \right] \quad (1.1)$$

where \vec{S}_N in the ^{60}Co spin, \vec{p}_e is emitted electron momentum. The last term in (1.1) implies parity nonconservation since spin does not change under reflection while momentum changes its sign. If parity conservation were true in β -decay, electron would have no preferred direction relative to \vec{S}_N and the last term in (1.1) would be equal to zero. Experimentally electrons were preferentially emitted in the direction opposite to that of the nuclear spin.

Not all topics covered in the lecture may be attributed to “new physics”, “Beyond the Standard Model”. For example, neutron lifetime puzzle may be either an experimental artifact, or the manifestation of mirror particles and mirror magnetic field. The quantum damping phenomenon presented at the end of the lecture is at the intersection of quantum mechanics and statistical physics. This effect may play a crucial role in future searches of neutron-antineutron oscillations, and, more generally, in flavor, or matter-antimatter oscillations.

The lecture is organized as follows. In the next section we discuss the neutron lifetime problem. Section 3 is devoted to the search for EDM of neutron. Section 4 contains the discussion of the CP symmetry in $n - \bar{n}$ oscillations. In Section 5 the quantum damping phenomenon is presented.

II. NEUTRON LIFETIME: BEAM VS BOTTLE

There is a long-standing controversy of experimental results for the neutron lifetime τ obtained by the two complementary methods: the beam and the storage (bottle) ones. The detailed description of the present situation and the historical retrospective may be found in three recent presentations [1–3].

Neutron lifetime τ is an important quantity for the CKM Unitarity test since τ^{-1} is proportional to $|V_{ud}|^2$. The theoretical uncertainty of $|V_{ud}|^2$ is $4 \cdot 10^{-4}$ and this imposes the requirement $\Delta\tau/\tau < 10^{-3}$. The primordial helium production is very sensitive to the value of τ and this brings a constraint on the baryon-to-photon ratio.

In the beam method protons from beta-decay of cold neutrons ($v \sim 10^3$ m/s) during its flight are counted. Absolute neutron flux must be measured very accurately. The beam method may overestimate τ if a fraction of beta-decay products is not detected. The best accuracy with the beam method was achieved in [4]

$$\tau = 887.7 \pm 2.3 \text{ s.} \quad (2.1)$$

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The current value based on two beam experiments is $\tau = 888.0 \pm 2.1$ s. [5].

The bottle method may be described as: fill-store-count. Use is made of ultracold neutrons (UCN, $v \sim 4$ m/s) trapped in a closed volume. The number of survived neutrons is measured as a function of time. The idea that UCN undergo a complete reflection from the trap material is due to Ya.B. Zeldovich (1959). In reality, a small fraction of UCN may be lost due to poorly controlled mechanisms. Therefore this method may underestimate the value of τ . Speaking about the bottled experiments, reference is most often is made to [6]

$$\tau = 878.5 \pm 0.8 \text{ s.} \quad (2.2)$$

The most recent storage value is [7]

$$\tau = 880.2 \pm 1.2 \text{ s.} \quad (2.3)$$

The current average result for the bottled experiments is $\tau = 879.6 \pm 0.8$ s [5]. Worth mentioning the preliminary result of Serebrov group with big gravitrap: $\tau = 875.9 \pm 1.5$ s [1]. Recently the first UCN magnetic storage result was obtained [8]

$$\tau = 878.3 \pm 1.9 \text{ s.} \quad (2.4)$$

The idea that low energy neutrons may be confined by magnetic field goes back to V.V. Vladimirovsky (1961).

From the above numbers it is clear that there is a severe discrepancy between beam and storage results. Loosely speaking, the standard Big Bang nucleosynthesis seems to favor beam results. Particle physics experiments tend to be in favor of the storage results. Ambitious plans for future precision measurements may be found in [1–3].

One may ask a question whether the above discrepancy may be a manifestation of some “new physics” playing a role only in one of the above methods. Here comes the hypothesis [9] that inside a trap neutrons may undergo oscillations into mirror neutrons which freely leave the trap. More than that, neutron-mirror-neutron oscillation frequency is sensitive to the direction of a hypothetical mirror magnetic field. The idea of mirror world was introduced by T.D. Lee and C.N. Yang in 1956 and developed by I.Yu. Kobzarev, L.B. Okun and I.Ya. Pomeranchuk in 1966. Necessary to note, however, that for the proposal [9] to work the oscillation time $\tau_{nn'}$ has to be as small as a few seconds. Present experimental lower limit on $\tau_{nn'}$ is $\tau_{nn'} > 414$ s [10]. According to [9] this result does not exclude the oscillation time to mirror neutrons of the order of a few seconds if the presence of mirror magnetic field is also assumed.

III. THE QUEST FOR EDM OF THE NEUTRON

During the last couple of years the new physics hopes at LHC have been fading fast. On the other hand, we observe the revival of the interest to possible manifestations of BSM (Beyond the Standard Model) in low energy physics. There is one effect the search for which lasts already for more than half a century. This is the electric dipole moment (EDM) of the neutron. The possibility of electric dipole moments for elementary particles was raised by E.M.Purcell and N.F.Ramsey in 1950: “The validity of P must rest on experimental evidence”. These great authors proposed neutron–beam resonance experiment for the detection of EDM.

The existence of neutron EDM would violate the CP –symmetry. To see this, consider the non-relativistic neutron Hamiltonian in an electromagnetic field

$$\hat{H} = -\mathbf{d}_n \mathbf{E} - \boldsymbol{\mu}_n \mathbf{B}, \quad (3.1)$$

where \mathbf{d} and $\boldsymbol{\mu}$ are the electric dipole and magnetic moments correspondingly (we use the natural system of units $\hbar = c = 1$, $\alpha = e^2/4\pi$). The only vector characteristic of the neutron is its spin \mathbf{S} , and therefore both \mathbf{d} and $\boldsymbol{\mu}$ should be either parallel, or antiparallel to \mathbf{S} . Under space and time inversion \mathbf{S} , \mathbf{E} and \mathbf{B} transform as

$$P : \mathbf{S} \rightarrow \mathbf{S}, \quad \mathbf{E} \rightarrow -\mathbf{E}, \quad \mathbf{B} \rightarrow \mathbf{B}, \quad (3.2)$$

$$t : \mathbf{S} \rightarrow -\mathbf{S}, \quad \mathbf{E} \rightarrow \mathbf{E}, \quad \mathbf{B} \rightarrow -\mathbf{B}. \quad (3.3)$$

Therefore the term $\mathbf{dE} \sim \mathbf{SE}$ violates both P - and T - symmetries, while the magnetic coupling given by the second term defines the neutron magnetic moment, $\mu_n = -1.91\mu_N$, $\mu_N = e/2m_p$. The observation of d_n would not only indicate the violation of P and T but the CP violation as well since any locally Lorentz–covariant theory with spin–statistics relation is CPT invariant. Since its discovery in K -decays in 1964, the CP violation has been thoroughly studied both experimentally (in particular in B -meson decays) and theoretically. The CP violation

is one of the three Sakharov conditions for Baryogenesis, in other words, for the explanation of matter-antimatter asymmetry in the Universe.

The neutron EDM is commonly measured in $e \cdot \text{cm}$. This correspond to a naive picture of two opposite charges separated by a distance $r(\text{cm})$. We refer to recent reviews [11, 12] for the description of the past, present and planned experiments aimed at the detection of the neutron EDM. The present upper limit on the neutron EDM is $3.0 \cdot 10^{-26} e \cdot \text{cm}$ (90% C.L.) [13, 14]. The measurement rests upon two basic elements : a) the use of UCN (the idea of F.L.Shapiro, 1969-1970), and b) the resonant frequency technique (N.F.Ramsey, 1950). For the detailed description see [11, 12]. Several new projects are under way.

In the SM the neutron EDM appears via the so-called penguin diagram [15] but its expectation value is very small $\sim 10^{-32} e \cdot \text{cm}$. Another possibility is to introduce into the QCD Lagrangian the θ -term which is odd under time reversal and thus breaks CP

$$L_\theta = \frac{\theta}{16\pi^2} \varepsilon^{\mu\nu\alpha\beta} G_{\mu\nu}^a G_{\alpha\beta}^a = \frac{\theta}{16\pi^2} G\tilde{G}, \quad (3.4)$$

where $G_{\mu\nu}^a$ is the gluon field tensor, \tilde{G} is its dual

$$G_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + igf^{abc} A_\mu^b A_\nu^c. \quad (3.5)$$

The θ -term is similar to **(EB)** product in electrodynamics.

However, from the experimental upper limit on d_n the value of θ should be tiny $\theta < 10^{-10}$. This situation is called the ‘‘Strong CP problem’’. We do not discuss d_n within the supersymmetric theories partly because no footprints of SUSY have been observed up to now.

Recently [16] a possibility that in strong magnetic field the induced neutron EDM is not generally constrained to lie along its spin has been discussed.

IV. $n\bar{n}$ - OSCILLATIONS AND CP VIOLATION

The observation of neutrons turning into antineutrons would constitute a discovery of fundamental importance for particle physics and cosmology. It would show that matter containing neutrons is unstable. The problem of $n\bar{n}$ -oscillations rises a lot of questions, both theoretical and experimental. The recent review of its theoretical status and experimental prospects may be found in [17].

The physical motivations for the search of $\Delta B \neq 0$ process is threefold:

- (i) Matter–antimatter asymmetry in the Universe,
- (ii) B -conservation is ‘‘accidental’’, no local $U(1)_B$ group unlike charge conservation with $U(1)_{\text{em}}$,
- (iii) In SM B is conserved only perturbatively – sphaleron breaks B but conserves $(B - L)$.

In this section we discuss only one side of the general $n\bar{n}$ oscillations problem, namely the possibility that oscillations imply the CP violation. This question was raised in [18] and followed by a vivid discussion [19, 20, 22]. We start by quoting the conclusions from [18] and [19]: ‘‘neutron–antineutron oscillation implies breaking of CP along with baryon number violation’’ [18], and ‘‘the neutron–antineutron oscillation per se does not necessarily imply CP violation’’ [19]. Below we follow in an oversimplified form the arguments presented in [19, 20]. A reasonable assumption is that Lorentz invariance and CPT are valid in a healthy field theory. The baryon number and parity symmetries are violated since $\Delta B = 2$ and parities of n and \bar{n} are opposite. The lagrangian with $\Delta B = 2$ term may be written in the following form

$$\begin{aligned} \mathcal{L} = & \bar{n}(x) i\gamma^\mu \partial_\mu n(x) - m\bar{n}(x)n(x) - \\ & - \frac{1}{2} [\varepsilon \bar{n}^c(x)n(x) + \varepsilon^* \bar{n}(x)n^c(x)]. \end{aligned} \quad (4.1)$$

The charge conjugation is defined by

$$\psi^c(x) = C\bar{\psi}^T(x), \quad \bar{\psi}^c(x) = \psi^T(x)C, \quad C = i\gamma^2\gamma^0. \quad (4.2)$$

The parity transformation is chosen as

$$\Psi(t, \mathbf{x}) \rightarrow \gamma_0 \Psi(t, -\mathbf{x}), \quad \bar{\psi}(t, \mathbf{x}) \rightarrow \bar{\psi}(t, -\mathbf{x})\gamma_0. \quad (4.3)$$

One may call this transformation γ^0 – parity in contrast to $i\gamma^0$ – parity used in some textbooks. In principle, one can add an extra mass term ($-m'\bar{n}i\gamma_5 n$) which we discard, see [18–21].

The first term in (4.1) is invariant under P , C and T . The second $\Delta B = 2$ term is P – odd.

What about the C – parity of this term? It is instructive to write ε in the form $\varepsilon = |\varepsilon|e^{i\alpha}$ with real α . Then for $\alpha = 0$ one retrieves the $\Delta B = 2$ Lagrangian of [18] which is obviously C even and thus CP odd. However, for $\alpha = \pi/2$ the second term in (4.1) is C odd and CP even. Physics seem to depend on phase rotation! In other words, the CP property of $\Delta B = 2$ term is ill-defined [19]. The deeper insight into the problem requires rather elaborate technique: Majorana fermions, inclusion of external fields, the spin dependence, Bogolyubov transformation, etc. [20, 22]. The general conclusion remains the same: the appearance of $n\bar{n}$ oscillations does not in itself break CP.

V. QUANTUM DAMPING OF $n\bar{n}$ OSCILLATIONS

The lower limit in $n\bar{n}$ oscillation time was set long ago in the ILL – Grenoble reactor experiment [23], $\tau_{n\bar{n}} > 0.86 \cdot 10^8 s$ (about 3 years), or $\varepsilon = \tau_{n\bar{n}}^{-1} < 10^{-23}$ eV. The internuclear experiments confirm this result up to a certain uncertainty due to the nuclear structure factors [17]. The “long” β -decay lifetime of the neutron $\lambda^{-1} = \tau_n = 0.88 \cdot 10^3 s$ (see Sec. II above) is 5 orders of magnitude less than $\tau_{n\bar{n}}$. In the energy scale ε is more than 16 orders of magnitude less than the Lamb shift in the hydrogen atom and about 10 orders of magnitude less than the hydrogen atom bouncer energy [24]. It is more correct therefore to use the term “rare decay” than oscillation.

What can lead to an additional suppression of this rare process? First, this is the splitting of n and \bar{n} states due to external magnetic field, $\omega = 2|\mu_n|B \simeq 6 \cdot 10^{-12}$ eV for the Earth magnetic field and $\omega \simeq 10^{-15}$ eV for $B \sim 10nT$ in the experiments [10]. The second suppression factor estimated in [10] as $\delta \sim 10^{-15}$ eV is due to the interaction with the residual gas. At this moment we discard this factor and will return to it shortly. With magnetic field included the expression for $n\bar{n}$ oscillations reads [17].

$$|\psi_{\bar{n}}(t)|^2 = \frac{4\varepsilon^2}{\omega^2 + 4\varepsilon^2} e^{-\lambda t} \sin^2 \left(\frac{1}{2} \sqrt{\omega^2 + 4\varepsilon^2} t \right). \quad (5.1)$$

Some refinements of this equation, like the wave packet formalism, may be found in [25–27]. The free-space regime $|\psi_{\bar{n}}(t)|^2 \simeq \varepsilon^2 t^2$ is “hidden” in (5.1) in the short time limit $t \ll 2/\omega$ provided $\varepsilon \ll \omega/2$. For $B \simeq 10^{-9}T$ foreseen in future experiments one has $2/\omega \simeq 0.2s$, $\omega/2 \simeq 3 \cdot 10^{-14}$ eV $\gg \varepsilon$. We note in passing that the $\varepsilon^2 t^2$ law does not allow to define the transition probability per unit time.

Now we consider in a schematic way the influence of environment on $n\bar{n}$ oscillations. It is possible to develop a general density matrix approach to $n\bar{n}$ oscillations when the role of the ambient medium is played by the trap walls, nuclear matter, or the residual gas inside the experimental setup. Here we consider only the residual gas case. Environment breaks the coherence [28] of the propagation making the description in terms of the wave function impossible. The problem of oscillations in a gas was first solved using the density matrix in [29] where muonium to antimuonium conversion was analyzed. For $n\bar{n}$ case similar approach has been developed in [30]. The two-state system is described by the density matrix.

$$\hat{\varrho} = \begin{pmatrix} \varphi_1 \varphi_1^* & \varphi_1 \varphi_2^* \\ \varphi_1^* \varphi_2 & \varphi_2 \varphi_2^* \end{pmatrix} = \begin{pmatrix} \varrho_{11} & \varrho_{12} \\ \varrho_{21} & \varrho_{22} \end{pmatrix}. \quad (5.2)$$

In vacuum and without decay $\hat{\varrho}$ satisfies the von Neumann-Liouville equation

$$i \frac{d\hat{\varrho}}{dt} = [\hat{H}, \hat{\varrho}], \quad (5.3)$$

$$\hat{H} = \begin{pmatrix} E + \Delta_1 & \varepsilon \\ \varepsilon & E + \Delta_2 \end{pmatrix}, \quad (5.4)$$

where $\Delta_1 - \Delta_2 = \omega$. Equation (5.3) may be represented in a vector form of the Bloch equation [31]. The real Bloch vector \mathbf{R} is introduced by the expansion of the density matrix over the Pauli matrices

$$\hat{\varrho} = \frac{1}{2}(1 + \mathbf{R}\boldsymbol{\sigma}). \quad (5.5)$$

Then

$$\mathbf{R} = \begin{pmatrix} \varrho_{12} + \varrho_{21} \\ -i(\varrho_{21} - \varrho_{12}) \\ \varrho_{11} - \varrho_{22} \end{pmatrix}. \quad (5.6)$$

The von Neumann-Liouville equation (5.3) may be written in the following form

$$\dot{\mathbf{R}} = \mathbf{V} \times \mathbf{R}, \quad (5.7)$$

$$\mathbf{V} = \begin{pmatrix} 2\varepsilon \\ 0 \\ \omega \end{pmatrix}. \quad (5.8)$$

Equation (5.7) describes the precession of \mathbf{R} around the ‘‘magnetic field’’ \mathbf{V} . Equations (5.3) and (5.7) does not include decoherence since they correspond to an isolated system. As before, in the short time limit they yield $\varrho_{22} \simeq \varepsilon^2 t^2$. Interaction with the environment destroys the off-diagonal elements of $\hat{\varrho}$ and this is the essence of decoherence. As a result the interference between the two basic states $|n\rangle$ and $|\bar{n}\rangle$ may become impossible.

Below we present an oversimplified scenario of oscillations damping. Let τ_i be the time interval between the $(i-1)$ -th and i -th collisions with the gas molecules. We also introduce the average time between collisions $\tau = t/n$, n is the number of collisions, t is the observation time. In this simple picture we do not care that in a real experiment n may be of the order of one, we only assume that $\varepsilon\tau \ll 1$, i.e., $\tau \ll 10^8$ s. To make things even simpler we ignore the external magnetic field and put $\omega = 0$. According to (5.7) and (5.8) the evolution of the system before the first collision proceeds according to

$$\dot{R}_z = 2\varepsilon R_y, \quad \dot{R}_y = -2\varepsilon R_z. \quad (5.9)$$

Then just before the first collision (5.9) yields

$$R_z(\tau_1) = \cos 2\varepsilon\tau_1, \quad R_y(\tau_1) = -\sin 2\varepsilon\tau_1. \quad (5.10)$$

At the collision the \bar{n} component gets annihilated while the n component is assumed to stay intact. Then just after the collision one has

$$R_z(\tau_1) = \cos^2 \varepsilon\tau, \quad R_y(\tau_1) = 0. \quad (5.11)$$

Note that τ_1 in (5.10) and (5.11) differ by the collision time which is discarded here. Under the assumption $\varepsilon\tau \ll 1$ and averaging over the time intervals between collisions one obtains [30, 32]

$$R_z = \prod_{k=1}^n \int_0^\infty \frac{d\tau_i}{\tau} \exp\left(-\frac{\tau_i}{\tau}\right) \cos^2(\varepsilon\tau_i) \simeq \exp(-2\varepsilon^2\tau t). \quad (5.12)$$

At this point we note that one can arrive at the result (5.12) if an additional damping parameter ϱ is introduced into (5.9), namely

$$\dot{R}_z = 2\varepsilon R_y, \quad \dot{R}_y = -2\varepsilon R_z - \varrho R_y. \quad (5.13)$$

The factor ϱ should not be confused with the β -decay parameter $\lambda = 1/\tau_\beta$ which enters into the equations for all three components of \mathbf{R} on equal footing (β -decay is temporary discarded). From (5.13) one obtains the following equation for R_z

$$\ddot{R}_z + \varrho\dot{R}_z + 4\varepsilon^2 R_z = 0. \quad (5.14)$$

In the limit $\varrho \gg \varepsilon$ the solution of (5.14) has the form

$$R_z \simeq \exp\left(-\frac{4\varepsilon^2}{\varrho}t\right). \quad (5.15)$$

The condition to match (5.12) is

$$\varrho = \frac{2}{\tau} \sim \nu v \sigma_a, \quad (5.16)$$

where ν is the number density of the residual gas molecules, v is the mean velocity between n and the gas molecules, σ_a is the annihilation cross section. For $\varrho \gg \varepsilon$ the solution (5.15) means that at any time

$$\left| \frac{\psi_{\bar{n}}(t)}{\psi_n(t)} \right|^2 \simeq \frac{4\varepsilon^2}{\varrho^2} \ll 1. \quad (5.17)$$

In terms of the Bloch vector the overdamping regime (5.15) means that due to annihilation R_z does not have enough time to turn from $R_z = 1, \varrho_{11} = 1, \varrho_{22} = 0$ to $R_z = -1, \varrho_{11} = 0, \varrho_{22} = 1$.

The overdamping regime previously discussed in [30, 33] and within the general theory of decoherence in [28]. Whether this regime might be of importance in already performed and planned experiments is a topic of a separate investigation.

The decoherence caused by the interaction with the environment is a general phenomenon. It takes place in neutrino oscillations [34], positronium [35] and neutron [36] oscillations to mirror, or brane worlds, heavy quarks oscillations in the color gluon field environment [37], B - and K -mesons oscillations [38, 39].

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