Search for EDMs using Storage Rings

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Abstract. Permanent electric dipole moments (EDMs) violate parity and time-reversal symmetry. Within the Standard Model (SM), they require CP violation and are many orders of magnitude below present experimental sensitivity. Many extensions of the SM predict much larger EDMs, which are therefore an excellent probe for the existence of new physics. Until recently it was believed that only electrically neutral systems could be used for sensitive searches of EDMs. With the introduction of a novel experimental method, high precision for charged systems will be within reach as well. The features of this method and its possibilities and status are discussed.

1. Introduction
The study of the discrete symmetries C (charge conjugation), P (parity), and T (time reversal) has been the source of some of the most important progress in the understanding of fundamental interactions during the past 50 years. Whereas C and P, and their product CP, are conserved in strong and electromagnetic interactions, they are violated in the weak interaction. The (maximal) violation of P and C are well understood as a result of the handedness of the weak interaction, but the origin and magnitude of CP-violation (CPV) remain among the most poorly understood features of the Standard Model.

The first evidence for CPV, in the neutral kaon system, was reported in 1964 [1]. It took until 1973 before Kobayashi and Maskawa proposed a model that incorporates CPV through an irreducible complex phase in the weak-interaction quark mixing matrix [2]. This idea, which was presented at a time when only the u, d, and s quarks were known to exist, was remarkable because it required the existence of six quarks, the last of which (the top-quark) was found in 1995. Only in 2001 CPV was found outside the kaon system, viz. in the (decay of the) B-meson [3, 4]. The observations were consistent with those predicted by the KM model, based on the earlier kaon measurements.

The baryon-antibaryon asymmetry in the universe (BAU) extracted from cosmological observations may provide another angle on CPV [5]. In his seminal paper, Sakharov showed that C and CP violation, together with non-conservation of baryon number and thermal non-equilibrium, may lead to a surplus of matter [6]. However, the amount of violation inferred from experiments using K and B mesons is insufficient to explain the cosmological asymmetry. For this and other reasons, the SM is believed to be incomplete, despite its enormous successes.

Closely related to CP-violation is the violation of time reversal symmetry (T). To date, no undisputed experimental evidence exists of TRV (time-reversal violation). The CPLEAR...
collaboration claimed the first observation of direct TRV [7, 8, 9], but their results relies on the assumption that the combined \( \mathcal{CPT} \) symmetry is conserved. With this assumption, CPV is equivalent to TRV. As CPV has been established experimentally, this assumption requires that TRV should also occur at some level. However, when relaxing the requirement that \( \mathcal{CPT} \) is conserved, all claimed evidence is ambiguous regarding the violation of \( \mathcal{CPT} \) or \( T \). Similar observations were made by the kTeV collaboration [10].

Many searches are underway worldwide to set more stringent limits on TRV. Three possible observables include [11]

- triple correlations in \( \beta \)-decay, e.g. the D-coefficient that measures the strength of the term \( \vec{J} \cdot (\vec{p}_e \times \vec{p}_\nu) \).
- permanent electric dipole moments on fundamental particles (and quantum systems with a non-degenerate ground state), i.e. \( \vec{d} \cdot \vec{E} \neq 0 \).
- “detailed balance” in scattering reactions, such as \( p + n \rightleftharpoons d + \gamma \).

The search for detailed balance is conceptually most easily understood as a test of time reversal invariance, as indeed the final and initial states are exchanged. However, the search for detailed balance is severely hampered by experimental complexity. The scattering cross section is dominated by electromagnetic and possibly strong interactions, on top of which a small weak interaction perturbation could lead to TRV. It is therefore not considered as a viable route for precise studies of TRV.

Experiments trying to observe non-zero triple-correlation amplitudes include the measurement of the electron spin and momentum correlation in muon and neutron decay, and various nuclear \( \beta \)-decay experiments [12]. Without TRV, the amplitude of the triple correlation term must be zero. The same holds for permanent electric dipole moments (EDMs), which can only have a non-zero magnitude if both parity and time-reversal symmetry are broken. As with triple correlation measurements, there are multiple efforts underway worldwide to search for a non-zero EDM or to set more stringent limits. I will concentrate on EDMs in the remainder of this paper.

2. The EDM landscape

That permanent electric dipole moments break both \( \mathcal{P} \) and \( \mathcal{T} \) is manifest when considering the field dependent part of the interaction Hamiltonian \( \mathcal{H} \) for a particle in an electric field \( \vec{E} \) and a magnetic field \( \vec{B} \),

\[
\mathcal{H} = - \left( \vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E} \right) = - \left( \mu \vec{B} + d \vec{E} \right) \cdot \frac{\vec{J}}{J}.
\]

The second equality holds because the direction of the spin \( \vec{J} \) is the only vector defining a direction in the rest frame of the particle. The electric and magnetic dipole moments must point along it; \( \mu = g(e\hbar/mc) \) and \( d = \eta/2(e\hbar/mc) \) are the respective proportionality constants. Under parity, \( \vec{E} \) reverses, while \( \vec{B} \) and \( \vec{J} \) remain unchanged; similarly, for time reversal \( \vec{B} \) and \( \vec{J} \) reverse, while \( \vec{E} \) remains unchanged. In both cases the Hamiltonian is altered, violating \( \mathcal{T} \) and \( \mathcal{P} \), unless \( d = 0 \).

Within the Standard Model, the symmetry properties of \( \mathcal{T} \) and \( \mathcal{CP} \) are equivalent, which implies particles may acquire non-zero EDMs through \( \mathcal{CP} \) violating radiative corrections of the electro-magnetic interaction vertex. To get non-canceling contributions, third or higher order loop corrections are necessary, which makes these EDMs extremely small and far below present detection limits [13]. In many proposed extensions of the SM, the need for higher-order is not present, and EDMs may occur even at first order [14]. With this in mind, the quest for a non-zero EDM is a background-free way to unambiguously establish the presence of physics beyond
Table 1. Overview of the most stringent experimental EDM limits (95% C.L.), the system in which they were measured, the Standard Model value and the largest, allowed, prediction from various SM extensions.

| particle | limit $[e \cdot cm]$ | system               | SM $[e \cdot cm]$ | New Physics $[e \cdot cm]$ | Reference |
|----------|-----------------------|----------------------|-------------------|-----------------------------|-----------|
| electron | $1.9 \times 10^{-27}$ | $^{205}$Tl atom      | $\sim 10^{-38}$   | $10^{-27}$                  | [16]      |
| muon     | $1.8 \times 10^{-19}$ | rest frame E field   | $\sim 10^{-35}$   | $10^{-22}$                  | [17]      |
| proton   | $7.9 \times 10^{-25}$ | $^{199}$Hg atom      | $\sim 10^{-31}$   | $5 \times 10^{-26}$         | [18]      |
| neutron  | $2.9 \times 10^{-26}$ | ultra cold neutrons  | $\sim 10^{-31}$   | $2.9 \times 10^{-26}$       | [19]      |
| $^{199}$Hg | $3.1 \times 10^{-29}$ | $^{199}$Hg atom      | $\sim 10^{-33}$   | $3.1 \times 10^{-29}$       | [18]      |
circumvents these problems and allows the EDM of charged particles to be measured directly [23]. This method provides direct access to the very interesting, so far unexplored, realm of light nuclei.

3. Spin precession in an electromagnetic storage ring
Magnetic storage rings and Penning traps have been used to precisely measure magnetic dipole moments, notably of the electron and muon [24, 25]. In the absence of an electric dipole moment, the spin evolution is described by the so-called BMT or Thomas equation,

$$\frac{d\vec{S}}{dt} = \frac{e}{mc} \vec{S} \times \left[ a\left(\vec{B} - \gamma \frac{\vec{E}}{\gamma + 1}\right) - \vec{\beta} \times \vec{E} \right] + \frac{1}{\gamma + 1} \vec{B} - \gamma \vec{\beta} \times \vec{E}$$

(2)

with the magnetic moment anomaly \(a = (g - 2)/2\), with \(g\) as defined in section 2. This equation simplifies considerably, if we consider the spin in a reference frame that rotates along with the particle as it goes around in a storage ring. Secondly, the magnetic field is usually orthogonal to the velocity, so that \(\vec{\beta} \cdot \vec{B} = 0\). In this case, equation (2) simplifies to

$$\frac{d\vec{S}}{dt} = \frac{e}{mc} \vec{S} \times \left[ a\vec{B} + \left(a - \frac{1}{\gamma^2 - 1}\right) \vec{\beta} \times \vec{E} \right].$$

(3)

For extremely low velocities, such as in a Penning trap, or for the magic momentum \(a - 1/\left(\gamma^2 - 1\right) = 0\), this simplifies even further to \(\frac{d\vec{S}}{dt} = \frac{ae}{mc} \vec{S} \times \vec{B}\).

When a non-zero EDM is assumed some additional terms appear,

$$\frac{d\vec{S}}{dt} = \frac{e}{mc} \vec{S} \times \left[ a\vec{B} + \left(a - \frac{1}{\gamma^2 - 1}\right) \vec{\beta} \times \vec{E} + \frac{\eta}{2} \left(\vec{E} + \vec{\beta} \times \vec{B}\right)\right] \equiv \vec{S} \times \vec{\Omega}.$$  

(4)

Several techniques can be devised to gain sensitivity to the EDM, three of which are outlined below.

3.1. The parasitic way
For relativistic particles, for which \(\beta \gg 0\), the motional electric field \(\vec{\beta} \times \vec{E}\) in the rest frame of the particle may be significant. Both the magnetic and electric dipole moments contribute to the precession \(\vec{\Omega} = \vec{\omega}_a + \vec{\omega}_\eta\). With the assumption that the average electric field in the laboratory system is zero, \(\vec{\omega}_a = (ae/mc)\vec{B}\) and \(\vec{\omega}_\eta = (\eta e/2mc)(\vec{\beta} \times \vec{B})\). These two components are orthogonal. The magnitude of the precession rate therefore depends on the EDM in second order,

$$\Omega = \sqrt{\omega_a^2 + \omega_\eta^2} \simeq \omega_a \left[ 1 + \frac{1}{2} \left(\frac{\eta \beta}{2a}\right)^2\right].$$

(5)

Furthermore, the precession plane, defined by the vector \(\vec{\Omega}\), is tilted with respect to the plane containing the orbits of the particles, defined by \(\vec{B}\). The tilt angle is

$$\phi = \arctan\frac{\omega_\eta}{\omega_a} \simeq \frac{\eta \beta}{2a}.$$  

(6)

Note that this tilt is always radially inward or outward.

At this point, two methods can be identified to search for an EDM. First one could very precisely measure the spin precession rate and account for the contribution from the anomalous magnetic moment, which would have to be calculated, or obtained by other means. Precise
calculations are only feasible for structureless particles, \textit{i.e.} leptons, and even then the most precise calculation has a precision of a few parts-per-billion (for the electron). As the EDM contributes only to second order, this precision is by far not enough for a competitive experiment on the electron. It should be noted though, that in the presence of an EDM the rate of precession always goes up. Model dependence can be removed by measuring the spin precession rate as a function of $\beta$.

The tilt in the precession plane gives a more solid and unambiguous handle on the EDM. Assuming that the initial polarization is entirely along the momentum, the components pointing along the magnetic field ($P_\parallel$, the EDM signal), pointing sideways ($P_\perp$) and along the momentum ($P_\leftrightarrow$, the anomalous magnetic moment signal), are respectively given as

\begin{align*}
P_\parallel(t) &= P_0 \frac{\omega_\eta}{\sqrt{\omega_\eta^2 + \omega_\eta^2}} \sin \sqrt{\omega_\eta^2 + \omega_\eta^2} t \simeq P_0 \frac{\eta}{2a} \sin \Omega t \\
P_\perp(t) &= P_0 \frac{\omega_\eta}{\sqrt{\omega_\eta^2 + \omega_\eta^2}} \sin \sqrt{\omega_\eta^2 + \omega_\eta^2} t \simeq P_0 \sin \Omega t \\
P_\leftrightarrow(t) &= P_0 \cos \sqrt{\omega_\eta^2 + \omega_\eta^2} t \simeq P_0 \cos \Omega t
\end{align*}

The last equalities hold to first order in $\eta$. In the absence of an EDM, the spin component along the magnetic field cannot be time dependent. The challenge lies in the determination of the orientation of the (effective) magnetic field. The only reported measurements of this kind have been made on the muon at CERN and later at Brookhaven [26, 17], with $d_\mu < 1.8 \times 10^{-19} \text{e} \cdot \text{cm}$ (95\% C.L.) as the final limit for the muon EDM.

The sensitivity of this method is limited, because the vertical polarization component can only grow for a time of the order of the precession period. The growth-time can be significantly increased if the contribution of the magnetic moment to the spin precession is reduced.

### 3.2. Frozen spin method

The sensitivity for an EDM is increased if $\omega_a \to 0$ (see equation (6)), in which case the growth of the vertical polarization component continues as long as the beam is polarized. The use of a radially oriented electric field $E_r$ was proposed in Ref. [23]. In the presence of an electric field, the contributions of the magnetic and electric dipole moments become

\begin{align*}
\vec{\omega}_a &= \frac{e}{mc} \left[ a \vec{B} + \left( a - \frac{1}{\gamma^2 - 1} \right) \vec{\beta} \times \vec{E} \right] \\
\vec{\omega}_\eta &= \frac{e}{mc} \frac{\eta}{2} \left( \vec{\beta} \times \vec{B} + \vec{E} \right)
\end{align*}

For a field strength given by

\begin{equation}
E_r = \frac{a B c \beta}{1 - (1 + a) \beta^2},
\end{equation}

$\omega_a$ can be made zero. At the magic momentum (as defined above), the denominator becomes zero; freezing the spin then requires $B = 0$. In that case any electric field strength can be used. Note that this requires $a > 0$.

The time evolution of the polarization becomes

\begin{align*}
P_\parallel(t) &= P_0 \sin \omega_\eta t \simeq P_0 \frac{\eta e}{4 m c} (\beta B + E_r) t \\
P_\perp(t) &= 0 \\
P_\leftrightarrow(t) &= P_0 \cos \omega_\eta t \simeq P_0
\end{align*}

The EDM thus manifests itself as a linearly growing vertical polarization component.
The strengths of this method lie in the fact that the growth time of the vertical spin component can be as long as the spin coherence time of the beam and that the electric field in the particle rest frame may be significantly larger than that applied in the laboratory frame, by a factor

$$\xi = \frac{\beta B_z + E_r}{E_r} = \frac{a + 1}{a^2}$$  \hspace{1cm} (11)

For particles with small $a$ and low $\gamma$ this amplification may be many orders of magnitude.

The statistical precision of this method depends on several factors, such as the initial polarization of the beam $P_0$, a characteristic time $T \simeq \sqrt{\tau \tau_p}$ determined by the beam lifetime $\tau$ and the polarization coherence time $\tau_p$, the effective strength of the electric field $E = (\beta c B_z - E_r) = \xi E_r$, the analyzing power $A$ and efficiency $\epsilon$ of the polarimeter, and the number of particles used to make the measurement $N = \epsilon N_{tot}$. The uncertainty on the measured EDM can be described in good approximation by

$$\sigma_d \simeq \frac{4\hbar}{P_0 E \sqrt{NTA}}$$  \hspace{1cm} (12)

One of the challenges of this method is the limited strength of the radial electric field. Therefore, this technique is optimal only for particles with small anomalous magnetic moments. Alternatively, particles with very low velocities may be used.

### 3.3. Spin resonance

The limitations imposed by the radial electric field can be avoided by yet another technique [27]. From equation (6), it follows that the tilt angle does depend on the velocity. A longitudinal electric field $E_{RF}$ may be used to modulate the velocity with amplitude $\delta \beta$ and frequency $\omega$. In this case, the spin motion is described by

$$\frac{d\vec{S}}{dt} = \vec{S} \times \frac{e}{mc} \left[ aB + \eta \left( \vec{\beta}_0 \times \vec{B} \right) + \eta \cos(\omega t + \phi) \left( \delta \vec{\beta} \times \vec{B} + \vec{E}_{RF} \right) \right]$$  \hspace{1cm} (13)

Because $\Omega \gg \delta \Omega$, the oscillating term can be treated as a perturbation. The vertical polarization component is given by

$$dP_\parallel/\,dt = \eta P_0 \delta \Omega \cos(\Omega t + \phi) \cos(\omega t + \psi) \simeq \frac{1}{2} \eta P_0 \delta \Omega \cos(\Delta \omega t + \Delta \phi) \,.$$  \hspace{1cm} (14)

In the last step, fast oscillating terms ($\propto \cos((\Omega + \omega)t)$) were omitted and it was assumed that $\Delta \omega \equiv \Omega - \omega \simeq 0$ and $\Delta \phi \equiv \phi - \psi \simeq 0$. For $\Delta \omega = 0$ the vertical polarization will grow continuously at a rate proportional to the EDM. Maximum sensitivity is obtained for $\Delta \phi = 0$ and $\Delta \phi = \pi$. In the latter case the sign of the growth is reversed.

The statistical sensitivity of this method is similar to that for the frozen spin method. In the latter, the EDM signal was proportional to $\vec{v} \times \vec{B}$. The magnitude of $B$ is restricted by the freezing condition and the maximum attainable electric field strength. In this method, no such limit is present, and the magnetic field strength can be raised as high as practical. So although the uncertainty is proportional to the amplitude of the velocity modulation $dv$, rather than $v$, the product $dv \times \vec{B}$ may be similar in size.

This method is suitable for all particles for which the synchrotron tune $\nu_l$ and spin tune $\nu_{spin} = a \gamma$ can be brought to resonance, i.e. $\nu_l - \nu_{spin} = n$ ($n$ integer). It is believed that besides the deuteron ($a = -0.143$) also other light ion EDMs might be within reach, such as the proton ($a = 1.79$) and helium $^3$He ($a = -4.19$).
4. Status and Prospects

To date, the only direct measurement of a charged particle EDM that reached reasonable precision was made for the muon ($|d_{\mu}| < 1.8 \times 10^{-19}\,e\cdot\text{cm}$), in an experiment aimed to measure the anomalous magnetic moment [17]. The EDM was extracted from the tilt in the spin precession plane (i.e. based on the parasitic method) and was statistics limited.

Several options are considered for a dedicated muon EDM search based on the frozen spin method. The first proposal was worked out for the upgraded J-PARC facility (expected 2015) [28]. It aims at a sensitivity at the level of $10^{-24}\,e\cdot\text{cm}$. A similar setup is considered as a successor to the muon $g−2$ experiment at FNAL [29]. In both experiments a muon momentum of about 500 MeV/c would be used. This results in a storage ring of several meter in diameter, determined by the limited electric field strength that is needed to freeze the spin.

A much smaller setup is possible when muons of much lower momentum are used. At $p = 125\,\text{MeV/c}$ a storage ring of less than 1 m diameter yields an intrinsic sensitive slightly above that found in the larger experiments [30]. The size is in this case determined by the maximum magnetic field strength rather than the electric field strength. With a single muon at a time (as feasible at the $\mu$E1 beamline of PSI), such an experiment could yield a limit of $5 \times 10^{-23}\,e\cdot\text{cm}$. At this level it is already possible to rule out hypothetical new theories that predict non-linear mass scaling of the leptonic EDM [31]. At a future high-power facility this limit could be further reduced by another two orders of magnitude [32].

The experience gleaned from such a small scale experiment would put the more demanding large scale experiments to search for EDMs in light nuclei on a much stronger footing. At Brookhaven National Laboratory an experiment on the proton at the level of $|d_p| \simeq 3 \times 10^{-29}\,e\cdot\text{cm}$ was proposed based on the frozen spin method with magic momentum protons ($p = 0.7\,\text{GeV/c}$), i.e. on a purely electrostatic storage ring. At an electric field strength of 15 MV/m such a ring would have an approximate circumference of 200 m. At the Forschungszentrum Jülich, the possibilities for a facility to search for EDMs on light nuclei, notably deuterons, are investigated [33]. A storage ring for deuterons as proposed in [34] to reach $|d_D| \simeq 10^{-29}\,e\cdot\text{cm}$ would fit inside the COSY ring, which could serve as the injector. Current R&D efforts are executed jointly, as many of the experimental challenges (such as high precision polarimetry, high electric field strength and long spin coherence time) are common to both efforts. For example, at COSY a method was demonstrated to reach a sensitivity to changes in the vertical polarization of $dP/P \sim 10^{-6}$, sufficient to reach the aimed-for EDM limit [35]. EDM measurements on the proton, deuteron and helion are complementary to each other and to those on the neutron and e.g. mercury and radium [36, 37, 38]. At the expected sensitivity of $|d| < 10^{-29}\,e\cdot\text{cm}$ the sensitivity for $\bar{\theta}$ and many proposed versions of new physics surpasses that of current or planned experimental limits.

In conclusion, storage rings make it possible to enter new territory in the search for EDMs. They make it possible to directly probe charged particles with competitive sensitivity, in particular the muon and light ions. Such systems have a complementary sensitivity to new sources of $\text{CP}$-violation and may help to pin-down the last unconfirmed source of $\text{CP}$-violation in the Standard Model, $\bar{\theta}$. Several possible experimental approached have been identified. The parasitic method will (again) be employed to improve the limit on the muon EDM. The frozen spin method is being investigated to search for the muon, proton and deuteron EDM. At the proposed sensitivities, these searches will have a major impact on our understanding of $\text{CP}$-violation.

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References

[1] Christenson J H, Cronin J W, Fitch V L and Turlay R 1965 Phys. Rev. 140 B74–B84
[2] Kobayashi M and Maskawa T 1973 Prog. Theor. Phys. 49 652–657
[3] Aubert B et al. (BABAR) 2001 Phys. Rev. Lett. 87 091801 (Preprint hep-ex/0107013)
[4] Abe K et al. (Belle) 2001 Phys. Rev. Lett. 87 091802 (Preprint hep-ex/0107061)
[5] Barger V, Kneller J P, Lee H S, Marfatia D and Steigman G 2003 Phys. Lett. B566 8–18 (Preprint hep-ph/0305075)
[6] Sakharov A D 1967 Pisma Zh. Eksp. Teor. Fiz. 5 32–35
[7] Angelopoulos A et al. (CLEO) 1998 Phys. Lett. B444 38–42
[8] Rouge A 1999 (Preprint hep-ph/9909205)
[9] Barger V, Kneller J P, Lee H S, Marfatia D and Steigman G 2003 Phys. Lett. B566 8–18 (Preprint hep-ph/0305075)
[10] Alavi-Harati A et al. (KTeV) 2000 Phys. Rev. Lett. 84 408–411 (Preprint hep-ex/9908020)
[11] Herczeg P 2001 Prog. Part. Nucl. Phys. 46 413–457
[12] Severijns N, Beck M and Naviliat-Cuncic O 2006 Phys. Lett. B444 38–42
[13] Bigi I I Y and Sanda A I 1999 Phys. Lett. B466 33–40
[14] Sakharov A D 1967 Pisma Zh. Eksp. Teor. Fiz. 5 32–35
[15] Angelopoulos A et al. (CLEO) 1998 Phys. Lett. B444 38–42
[16] Rouge A 1999 (Preprint hep-ph/9909205)
[17] Barger V, Kneller J P, Lee H S, Marfatia D and Steigman G 2003 Phys. Lett. B566 8–18 (Preprint hep-ph/0305075)
[18] Sakharov A D 1967 Pisma Zh. Eksp. Teor. Fiz. 5 32–35
[19] Angelopoulos A et al. (CLEO) 1998 Phys. Lett. B444 38–42
[20] Rouge A 1999 (Preprint hep-ph/9909205)
[21] Barger V, Kneller J P, Lee H S, Marfatia D and Steigman G 2003 Phys. Lett. B566 8–18 (Preprint hep-ph/0305075)
[22] Sakharov A D 1967 Pisma Zh. Eksp. Teor. Fiz. 5 32–35
[23] Angelopoulos A et al. (CLEO) 1998 Phys. Lett. B444 38–42
[24] Rouge A 1999 (Preprint hep-ph/9909205)
[25] Barger V, Kneller J P, Lee H S, Marfatia D and Steigman G 2003 Phys. Lett. B566 8–18 (Preprint hep-ph/0305075)
[26] Sakharov A D 1967 Pisma Zh. Eksp. Teor. Fiz. 5 32–35
[27] Angelopoulos A et al. (CLEO) 1998 Phys. Lett. B444 38–42
[28] Rouge A 1999 (Preprint hep-ph/9909205)
[29] Barger V, Kneller J P, Lee H S, Marfatia D and Steigman G 2003 Phys. Lett. B566 8–18 (Preprint hep-ph/0305075)
[30] Sakharov A D 1967 Pisma Zh. Eksp. Teor. Fiz. 5 32–35
[31] Angelopoulos A et al. (CLEO) 1998 Phys. Lett. B444 38–42
[32] Rouge A 1999 (Preprint hep-ph/9909205)
[33] Barger V, Kneller J P, Lee H S, Marfatia D and Steigman G 2003 Phys. Lett. B566 8–18 (Preprint hep-ph/0305075)
[34] Sakharov A D 1967 Pisma Zh. Eksp. Teor. Fiz. 5 32–35
[35] Angelopoulos A et al. (CLEO) 1998 Phys. Lett. B444 38–42
[36] Rouge A 1999 (Preprint hep-ph/9909205)
[37] Barger V, Kneller J P, Lee H S, Marfatia D and Steigman G 2003 Phys. Lett. B566 8–18 (Preprint hep-ph/0305075)
[38] Sakharov A D 1967 Pisma Zh. Eksp. Teor. Fiz. 5 32–35
[39] Angelopoulos A et al. (CLEO) 1998 Phys. Lett. B444 38–42
[40] Rouge A 1999 (Preprint hep-ph/9909205)
[41] Barger V, Kneller J P, Lee H S, Marfatia D and Steigman G 2003 Phys. Lett. B566 8–18 (Preprint hep-ph/0305075)