Available online at www.sciencedirect.com

ScienceDirect

Nuclear Physics A 928 (2014) 116–127

NUCLEAR PHYSICS A

www.elsevier.com/locate/nuclphysa

Electric dipole moments of the nucleon and light nuclei

Andreas Wirzba

Forschungszentrum Jülich, Institut für Kernphysik, Institute for Advanced Simulation, and Jülich Center for Hadron Physics, D-52425 Jülich, Germany

Received 17 March 2014; accepted 5 April 2014

Available online 18 April 2014

Abstract

The electric dipole moments of the nucleon and light ions are discussed and strategies for disentangling the underlying sources of CP violation beyond the Kobayashi–Maskawa quark-mixing mechanism of the Standard Model are indicated. Contribution to *"45 years of nuclear theory at Stony Brook: a tribute to Gerald E. Brown"*.

Keywords: Electric dipole moments; CP violation; Chiral perturbation theory

1. Prologue

I came to Gerry Brown's group in 1982 as a visiting graduate student on a one-year scholarship of the *Studienstiftung des deutschen Volkes* on recommendation of Achim Richter and Hans A. Weidenmüller. Gerry with his *big heart* readily integrated me in his group and eased my way into the graduate school in Stony Brook. He immediately put me on a project about pion-absorption on heavy nuclei which he, Wolfram Weise and Hiroshi Toki had been working on for some time. As I could correct some mistakes in the evaluation of the branching ratios, I earned—according to Gerry—my place as a co-author on a common paper which was published already in 1982. It was my highest cited paper for quite a while. After extending this work to ^{4}He together with the late Bernd Schwesinger, I then gradually entered the world of skyrmions and Casimir calculations of the chiral bag which blossomed during my stay at NORDITA and the Niels-Bohr-Institute from summer 1983 to 1984. Gerry moved with his 'cloud' of students (which included Ulf Meißner and Dubravko Klabucar) to Copenhagen, where I also met Ismail Zahed who was then a new postdoc hired by Gerry.

http://dx.doi.org/10.1016/j.nuclphysa.2014.04.003
0375-9474/

I have always admired Gerry's intuition which enabled him, without nearly any mathematical apparatus, to grasp the essentials of physics phenomena and to predict even the correct sign and magnitude. As far as I know, Gerry had never worked on electric dipole moments (EDMs), maybe because of his correct intuition that a positive EDM measurement of any subatomic particle will not materialize in his lifetime. I am also not sure whether I will see one. Well, as in any conference, there has to be a talk which Gerry would be least interested in. I am afraid that it could be mine, however, unfortunately we cannot ask him for his opinion any longer....

2. Motivation: matter–antimatter asymmetry in the universe

No matter how much *matter* in comparison to *antimatter* might have been created at the big bang itself, at the end of the inflation epoch the baryon–antibaryon (density) asymmetry must have been diluted to a high precision: $n_B = n_{\bar{B}}$. However, about $3.8 \cdot 10^5$ years later, when electrons and protons combined to form the first hydrogen atoms such that the corresponding photons could 'freeze' out from the evolution of the universe, this asymmetry—weighted relative to the photon density n_γ—acquired the following value

$$\left.\frac{n_B - n_{\bar{B}}}{n_\gamma}\right|_{\text{CMB}} = (6.08 \pm 0.09) \cdot 10^{-10}.$$

This was inferred from the cosmic microwave background (CMB) measurements by the COBE and WMAP satellite missions, where the displayed value is from a recent update [1]. The above displayed number has to be compared with the prediction of the Standard Model (SM) of particle physics which is about 7 orders of magnitude less, $n_B/n_\gamma|_{\text{CMB}} \sim 10^{-18}$, where this value follows from the incorporation of the determinant [2] of the Cabibbo–Kobayashi–Maskawa (CKM) quark-mixing matrix [3,4] of the SM.

In 1967 the eminent Russian physicist Andrey Sakharov [5] formulated three conditions for the dynamical generation of net baryon number during the evolution of the universe:

1. There has to be a mechanism for the generation of baryon charge B in order to depart from the initial value $B = 0$ (after the inflation epoch).
2. There should be C and CP violation to distinguish the rates of B production from the $\bar{B}$ production.
3. The dynamical generation had to take place during a stage of non-equilibrium, as otherwise the time-independence in the equilibrium phase would induce, under the assumption that CPT invariance holds, CP invariance in the average, such that also $\langle B \rangle = 0$ holds in the average.

Whereas B violation, more precisely, baryon plus lepton number violation $B + L$ can be accommodated by the Standard Model via the sphaleron mechanism at early temperatures $\sim$1 TeV, the other two conditions cannot be met by the SM, since the CP breaking by the Kobayashi–Maskawa (KM) mechanism [4] of the SM is too small and since the SM at vanishing chemical potential shows only a rapid cross over instead of a phase transition of first order. Therefore, the matter–antimatter asymmetry together with the insufficient CP violation of the SM is one of the few existing indicators that there might be physics beyond the Standard Model (BSM physics).