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AXIONS, GHOSTS, AND PSEUDOSCALARS AT LEAR

E. Gabathuler and G. Veneziano

CERN, Geneva, Switzerland

P. Pavlopoulos^{*)}

Institute of Physics, University of Basle, Basle, Switzerland

ABSTRACT

The intense and clean flux of pseudoscalar mesons at LEAR, the low-energy antiproton ring at CERN, allows for precise tests of the chiral predictions of the standard model.

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^{*)} Visitor at CERN, Geneva, Switzerland.

Quantum chromodynamics (QCD) appears today, more than ever before, as the leading candidate theory of strong interactions. Yet precise, quantitative tests of this highly non-trivial gauge theory are not easy to define. For instance, checks of the short distance properties of QCD, by e^+e^- or lepton-hadron high-energy collisions, suffer from experimental and theoretical uncertainties.

A welcome exception to this uncomfortable state of affairs is offered by the "chiral" predictions of QCD, resulting from the partial conservation of its axial currents (PCAC). Furthermore, the precise form of these predictions has been shown to test crucially the non-Abelian gauge structure of the gluonic (colour) interaction and its interplay with the $SU(2)_L \times U(1)$ Glashow-Weinberg-Salam (GWS) theory of electroweak phenomena.

Indeed, two experimental facts can be shown to put severe constraints on any candidate gauge theory of strong interactions. The first is the spectrum of the light pseudoscalar mesons, with $m_\pi \ll m_\eta \ll m_\eta'$, with a small ($\sim 10^\circ$) octet-singlet mixing; the second is the apparently exact conservation of CP in strong interactions, for which the upper bound on the electric dipole moment of the neutron [1] ($D_n < 6 \times 10^{-25} \text{ e}\cdot\text{cm}$) provides the most sensitive test to date. These two theoretical problems, usually referred to as the U(1) [2-4] and the strong CP problem [5] respectively, are perhaps surprisingly, intimately related.

The standard model claims to be able to solve the U(1) problem [6], since out of its nine axial currents

$$J_\mu^{(i,j)} \equiv \bar{\psi}_i \gamma_\mu \gamma_5 \psi_j ; \quad i,j = u,d,s \quad (1)$$

only eight are conserved in the limit of vanishing u -, d -, and s -quark masses; the ninth [U(1)] current has an anomalous divergence equation, related to quark-antiquark annihilation into gluons.

The actual solution of the U(1) problem requires [3,7,8] the colour self-interaction of the gluons to be such as to give a phantom gluonic bound state, the (axial) ghost. This massless object, rather than appearing as a pole in

physical amplitudes, prevents some of them from vanishing. Thus the ghost adds to the naïve Okubo-Zweig-Iisuka (OZI) conserving pseudoscalar mass matrix $\mu_i^2 \delta_{ij}$ (illustrated in fig. 1a) an extra, factorized OZI-violating contribution (fig. 1b). The phenomenology of the pseudoscalar nonet requires a ghost pseudoscalar coupling $\sqrt{a}$ of about 0.50 GeV [7,8].

Unfortunately, this elegant solution of the U(1) problem brings on the strong CP problem [5] discussed previously. The reason is that a new term can be added to the QCD Lagrangian which, in spite of being a total divergence, gives non-vanishing effects just because of the ghost. The new term contains a new parameter, the vacuum angle θ [6,9-12], and violates CP unless $\theta = 0$ or π . The value of θ is related to possible phases in the quark mass matrix. In the GWS model θ is expected to be of the order of unity, resulting in a neutron dipole moment $D_n \approx 10^{-14} - 10^{-13}$ e·cm, i.e. ten orders of magnitude larger than the present upper bound. In order to reduce D_n to an acceptable level a symmetry, or more precisely a classical U(1) symmetry, of the standard model is required which is broken at the quantum level by the colour (gluonic) anomaly. One way to achieve this is to make the u quark massless, but this is ruled out from PCAC considerations ($K^\pm - K^0$ mass difference, $\eta \rightarrow 3\pi$, etc.) [13]. With the standard quark mass values D_n is reduced, but still predicted [14,15] to be about $3.5 \times 10^{-16} \times \theta$ e·cm, i.e. about nine orders of magnitude too large for θ of the order of one. The only other possibility [16] is to modify, i.e. enlarge, the Higgs sector of the standard model, which gives a new U(1) symmetry. The Goldstone boson of this extra symmetry is the axion [17,18].

In the original Peccei-Quinn (PQ) proposal [16] two (instead of one) Higgs doublets ϕ_u and ϕ_d are introduced, giving mass to charged $+2/3$ and $-1/3$ quarks, respectively. Their expectation values break $SU(2) \times U(1)$ to $U(1)_{e1}$ and can be parametrized as

$$\langle \phi_u \rangle = \left(G_F \sqrt{2} \right)^{-\frac{1}{2}} \sin \alpha, \quad \langle \phi_d \rangle = \left(G_F \sqrt{2} \right)^{-\frac{1}{2}} \cos \alpha, \quad (2)$$

with $x = \cot \alpha$, the ratio of the vacuum expectation values of the two Higgs fields.

In order to make the axion harder to detect, Dine, Fischler and Srednicki [19] (DFS) have introduced a further Higgs field ϕ which, being a singlet of the symmetry group $SU(3) \times SU(2) \times U(1)$, does not break $SU(2)_L \times U(1)$ and can break the PQ symmetry at a scale $F \equiv \langle \phi \rangle$, much bigger than m_W .

In both axion models the axion's mass and mixing come from its coupling to the ghost as shown in fig. 2. The number ρ appearing in the coupling is easy to compute in any given axion model, e.g.

$$\rho = \left(x + \frac{1}{x} \right) N F_\pi G_F^{\frac{1}{2}} 2^{-\frac{1}{2}} = 2.7 \times 10^{-4} \left(x + \frac{1}{x} \right) N \quad \text{for the PQ model ,} \quad (3)$$

and

$$\rho = 2^{\frac{1}{2}} F_\pi F^{-1} N \quad \text{for the DFS model ,}$$

where N is the number of families and $F_\pi = 96$ MeV. The axion mass is then

$$m_{\pi_\alpha} = \rho \left(\frac{1}{a} + \sum_j \frac{1}{\mu_j^2} \right)^{-\frac{1}{2}} \approx 50N \left(x + \frac{1}{x} \right) R^{\frac{1}{2}} \text{ keV} \quad (\text{PQ})$$

(4)

or

$$100N R^{\frac{1}{2}} \left(\frac{250 \text{ GeV}}{F} \right) \text{ keV} \quad (\text{DFS})$$

where we have used $\mu_j^2 \propto m_j$ with $m_s \gg m_{u,d}$ and $R \equiv m_u m_d / (m_u + m_d)^2$. In the following, $2m_u = m_d$, $R = 0.22$, and $N = 3$ are adopted. The 2γ lifetime of the axion is predicted to be [17-19]:

$$\tau_{\gamma\gamma} = 7 \times 10^{-5} \left(\frac{1 \text{ MeV}}{m_{\pi_\alpha}} \right)^5 \text{ s} = 7 \left(\frac{100 \text{ keV}}{m_{\pi_\alpha}} \right)^5 \text{ s} , \quad (5)$$

hence the axion can be considered as a stable particle for our purpose.

In order to study the production of flavourless pseudoscalar particles and axions, it is necessary to have a high-yield clean source of pseudoscalar mesons, which can be achieved at LEAR, the Low-Energy Antiproton Ring at CERN [20]. In this case, the dominant production mechanism goes via an intermediate pure $q\bar{q}$ pseudoscalar state or via the ghost, followed by mixing and decay into the physical π^0, η^0, η' , and axion.

For the process $\bar{p}p \rightarrow \pi_{\alpha,\beta} + X$, where π_{α} represents an axion, π_{β} represents π^0, η, η' , and X represents $\pi^+\pi^-$, then the physical amplitudes are

$$M(\bar{p}p \rightarrow \pi_{\alpha} + X) = \sum_{i=u,d,s} C_{\alpha,i} A(\bar{p}p \rightarrow X + P_i) + C_{\alpha} A(\bar{p}p \rightarrow X + \text{ghost}), \quad (6)$$

$$M(\bar{p}p \rightarrow \pi_{\beta} + X) = \sum_{i=u,d,s} C_{\beta,i} A(\bar{p}p \rightarrow X + P_i) + C_{\beta} A(\bar{p}p \rightarrow X + \text{ghost}), \quad (7)$$

where A is the production amplitude for the unmixed pseudoscalars P_i ($i = u, d, s$) and the ghost. The parameters $C_{\beta,i}$ and C_{β} are given in table 1, and the axion coefficients are given by

$$C_{\alpha,u} = -\rho \left[\frac{m_d}{m_d + m_u} - \frac{1}{N} \frac{X^2}{1 + X^2} \right], \quad C_{\alpha,d} = -\rho \left[\frac{m_d}{m_d + m_u} - \frac{1}{N} \frac{1}{1 + X^2} \right], \quad (8)$$

with $C_{\alpha} \ll C_{\alpha,u}, C_{\alpha,d}$. From table 1, it can be seen that η' production is mediated mainly via the ghost and the π^0 production is insensitive to it. Measurements of the processes $\bar{p}p \rightarrow \pi^+\pi^- + \pi^0, \eta^0, \eta'$ in the "soft meson" region provide a useful test of the ghost contribution to the relative production of these mesons. In fact the π^0, η^0, η' productions are expected to be in the ratio of 0:0.15:1 if the ghost contribution dominates and 3.6:1.4:1 if P_u dominates.

A similar model has been used successfully [21] to predict the ratio $\Gamma(J/\psi \rightarrow \gamma\eta)/\Gamma(J/\psi \rightarrow \gamma\eta')$, where because of the initial $\bar{c}c$ state, only the ghost amplitude contributes in an equation similar to eq. (7). The possibility of searching for PQ axions in J/ψ and T radiative decays has already been pointed out [22]. The present experimental limit [22] for the branching ratio is $BR(J/\psi \rightarrow \gamma\pi_{\alpha}) < 3 \times 10^{-5}$.

Although there have been further attempts to study a harmless axion [23], i.e. very small coupling, the *raison d'être* for this appears to be based on its non-observation rather than any rigorous theoretical basis. In addition, attempts to avoid axions completely appear to raise fundamental problems by predicting the existence of massless quarks. Any experimental test which can put stringent

limits on axion production related to a well-defined mechanism for pseudoscalar production should therefore be carried out. In addition, the possibility of looking for a well-defined missing mass and missing energy independently of decays and branching ratios is very attractive provided $m_{\pi_\alpha} \lesssim 2m_e$. For axions of mass $m_{\pi_\alpha} > 2m_e$, electron-pair decay is a good signature for the exclusive detection $\pi_\alpha \rightarrow e^+e^-$ with a lifetime [21]

$$\tau_{ee} = \frac{10^{-9} \text{ MeV}^3}{m_{\pi_\alpha}^2 \left(m_{\pi_\alpha}^2 - 4m_e^2 \right)^{\frac{1}{2}}} \times^2 \text{ s} . \quad (9)$$

In the case of LEAR, the s-wave annihilation at rest process $\bar{p}p \rightarrow \pi^+\pi^- + \text{axion}$ is particularly interesting, since theoretical models [24] and data strongly infer that axions originate from the pure $\bar{u}u$ state as illustrated in fig. 3. This is confirmed by the 3:1 ratio of $\pi^0:\eta^0$ rates for the non-resonating part and is also approximately true for the resonating $\pi^+\pi^- (\rho^0)$ reflecting the higher probability of a $\bar{u}u$ rather than a $\bar{d}d$ final state of $\bar{p}p$ annihilation at rest. Using this simplification, hence just eq. (8), for $C_{\alpha,u}$ we get

$$R_{\pi_\alpha} = \frac{\sigma(\bar{p}p \rightarrow \pi^+\pi^- + \text{axion})}{\sigma(\bar{p}p \rightarrow \pi^+\pi^- + \pi^0)} > 1.2 \times 10^{-6} \quad \text{for a PQ axion}$$

and

$$6 \times 10^{-7} \left(\frac{250 \text{ GeV}}{F} \right)^2 < R_{\pi_\alpha} < 2.4 \times 10^{-6} \left(\frac{250 \text{ GeV}}{F} \right)^2 \quad \text{for a DFS axion} .$$

According to existing data [25,26], the yields of the reactions $\bar{p}p \rightarrow \pi^+\pi^-\pi^0$ and $\pi^+\pi^-\eta^0$ at rest are $6.9 \pm 0.5\%$ and $1.26 \pm 0.13\%$, respectively. Assuming a flux of $10^6 \bar{p}/s$ at LEAR, the pseudoscalar rates produced in the $\pi^+\pi^-\pi^0$ channel are $\sim 6 \times 10^9$ per day, giving rise to an axion rate (PQ type) of 10^4 per day. In addition, the annihilation channels $\pi^+\pi^-(2\pi^0)$ and $\pi^+\pi^-(3\pi^0)$ are $9.3 \pm 3.0\%$ and $23.3 \pm 3.0\%$, respectively, which would give an order of magnitude increase in the axion rate relative to $\pi^+\pi^-\pi^0$ production, as well as providing different final-state topologies for confirmation.

In order to investigate ghost effects in the reactions $\bar{p}p \rightarrow \pi^+\pi^- + \pi^0, \eta^0, \eta'$ and to search for axions, it is necessary to have a magnetic field volume to define the missing mass opposite to the two charged pions and to have a very good detection of gamma-rays both in energy and position. The advantage of this experiment using $\bar{p}$ at rest is that there is only 1.8 GeV of energy available for all the final-state particles. The maximum momentum of the charged particles is 800 MeV/c and therefore it is possible to achieve a missing-mass resolution ($\sigma \approx 20$ MeV) using standard proportional chamber/magnetic spectrometer techniques ($\Delta p/p \approx 1\%$) which give a clean separation of π^0, η^0 , etc., including lower masses. At these very low energies, the measurement of specific ionization can be easily achieved, thus separating pions and kaons. Kaons can also be excluded by kinematic constraints.

For the detection of neutral gamma-rays of energies in the region of 5 to 1000 MeV it is possible to use an electromagnetic calorimeter having an energy resolution $\approx 0.02 E^{-1/2}$. This can be achieved by using NaI or BGO modular detectors. The detection of π^0, η^0 , and η' states can easily be achieved through their neutral and charged particle decays in order to assist the missing-mass technique and provide on-line calibration. The search for axions can be extended to very low limits by demanding that no photon energy is observed in the electromagnetic calorimeter. The possibility that a $\pi^0 \rightarrow 2\gamma$ has not been observed is $\sim 10^{-10}$ for a detector of 20 radiation lengths, where both photons pass through the detector. For a detector of this size and by taking into account the electromagnetic suppression factor for direct photons, the probability that a photon from the reaction $\bar{p}p \rightarrow \pi^+\pi^-\gamma$ is not observed can be as small as 10^{-10} per $\bar{p}$ annihilation.

It is therefore apparent that it is possible to study in detail pseudoscalar production from $\bar{p}p$ annihilation at rest. The intensity of stopped $\bar{p}$ at LEAR ($\sim 10^6/s$) provides a unique method of studying rare processes such as axion production, etc., which can be achieved in a modest-sized detector of modest momentum resolution, but with good photon resolution because of the low energies

involved. Clearly the fact that $\bar{p}p$ at rest is a copious source of $\bar{u}u$ annihilations means that it is possible to study rare processes using modest compact detectors at the level of 10^{-10} of the $\bar{p}$ annihilation rate. The ghost mechanism in pseudoscalar and axion production is a good example of such studies, but the extension to low-mass glueballs or other exotic particles predicted from higher or supersymmetries is also possible.

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Table 1

Mixing coefficients $C_{\beta,i}$ and C_{β} , where β stands for a π^0 , η , or η' and i for a u, d, s, or ghost

$\beta \backslash i$	u	d	s	$\frac{\text{ghost}}{\sqrt{a}}$
π^0	$1/\sqrt{2}$	$-1/\sqrt{2}$	-0.013	0.024
η	0.44	0.44	-0.85	0.53
η'	0.37	0.37	0.72	1.38

Figure captions

- Fig. 1 : a) OZI-conserving part of the pseudoscalar mass matrix.
b) The OZI-violating ghost contribution.
- Fig. 2 : a) Axion pseudoscalar mixing through the ghost.
b) Axion self-energy through the ghost.
- Fig. 3 : Presumed dominant mechanism in $\bar{p}p|_{\text{rest}} \rightarrow \pi^+\pi^- + \pi_{\alpha,\beta}$.

(a)

(b)

(a)

(b)

The diagram illustrates the production of a neutral meson ($\pi^0, \eta, \eta', \text{axion}$) from a proton-antiproton annihilation. The initial state consists of a proton (P) and an antiproton ($\bar{P}$). The proton is composed of two up quarks (u) and one down quark (d), while the antiproton is composed of two anti-up quarks ($\bar{u}$) and one anti-down quark ($\bar{d}$). The annihilation process involves the exchange of a quark between the proton and antiproton, leading to the formation of a neutral meson. The diagram shows the quark lines and the resulting meson production, with coupling constants $C_{\alpha,u}, C_{\beta,u}$ indicated for the vertices.

Fig. 3