A New Light Boson?

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It is pointed out that a global U(1) symmetry, that has been introduced in order to preserve the parity and time-reversal invariance of strong interactions despite the effects of instantons, would lead to a neutral pseudoscalar boson, the "axion," with mass roughly of order 100 keV to 1 MeV. Experimental implications are discussed.

One of the attractive features of quantum chromodynamics[1] (QCD) is that it offers an explanation of why C, P, T, and all quark flavors are conserved by strong interactions, and by order-α effects of weak interactions.[2] However, the discovery of quantum effects[3] associated with the "instanton" solution of QCD has raised a puzzle with regard to P and T conservation. Because of Adler-Bell-Jackiw anomalies, the chiral transformation which is needed in QCD to bring the quark-mass matrix to a real, diagonal, γ_5-free form will in general change the phase angle θ associated[3] with instanton effects, leaving $\overline{\theta} \equiv \theta + \arg\det m$ invariant. [Here m is the coefficient of $\frac{1}{2}(1+\gamma_5)$ in a decomposition of the quark-mass matrix into $\frac{1}{2}(1\pm\gamma_5)$.] The condition for P and T conservation is that $\theta = 0$ when the quark fields are defined so that m is real, or more generally, that $\overline{\theta} = 0$. But θ is a free parameter, and in QCD there is no reason why it should take the value $-\arg\det m$. Furthermore, even if we simply demanded that the strong interactions in isolation conserve P and T, so that $\overline{\theta} = 0$, there would still be a danger that the weak interactions would introduce P- and T-nonconserving phases of order $10^{-3}\alpha$ in m, leading to an unacceptable neutron electric dipole moment, of order 10^{-18} $e\cdot$cm.

An attractive resolution of this problem has been proposed by Peccei and Quinn.[5] They note that the quark-mass matrix is a function $m(\langle\varphi\rangle)$ of the vacuum expectation values of a set of weakly coupled scalar fields φ_i. Although θ is arbitrary, $\langle\varphi\rangle$ is not; it is determined by the minimization of a potential $V(\varphi)$ which depends on θ. Peccei and Quinn assume that the Lagrangian has a global U(1) chiral symmetry [which I will call U(1)_{PQ}], under which $\det m(\varphi)$ changes by a phase. The phase of $\det m(\varphi)$ at the minimum of $V(\varphi)$ is then undetermined in any finite order of perturbation theory, and is fixed only by instanton effects which break the U(1)_{PQ} symmetry. However, the potential will then depend on $\overline{\theta}$, but not separately on θ and $\arg\det m$, so that it is not a miracle if the phase of $\det m(\varphi)$ at the minimum of $V(\varphi)$ happens to have the P- and T-conserving value $-\theta$. Peccei and Quinn[5] show in a number of examples that this is just what happens.

Now, the U(1)_{PQ} symmetry of the Lagrangian is intrinsically broken by instantons, and so at first sight one might not expect that it would have any further physical consequences. Certainly it does not lead to the strongly interacting isoscalar pseudoscalar meson below $\sqrt{3}m_\pi$,[6] that was the bugbear of the old U(1) problem. However, the scalar fields φ do not know about instantons, except through a semiweak ($\propto G_F^{1/2}$) coupling to quarks. Hence the spontaneous breakdown of the chiral U(1)_{PQ} symmetry associated with the appearance of nonzero vacuum expectation values $\langle\varphi\rangle$ leads[7] to a very light pseudoscalar pseudo-Goldstone boson,[8] the "axion," with m_a^2 proportional to the Fermi coupling G_F.

For insight in to the properties of the axion, it is useful to examine how they appear in the simplest realistic model that admits a U(1)_{PQ} symmetry. We assume an $\text{SU(2)}\otimes\text{U(1)}$ gauge group, with quarks in $N/2$ left-handed doublets and N right-handed singlets, and just two scalar doublets $\{\varphi_i^+, \varphi_i^0\}$, carrying U(1)_{PQ} quantum numbers such that φ_1 (φ_2) couples right-handed quarks of charge $-\frac{1}{3}$ ($+\frac{2}{3}$) to left-handed quarks. By writing the Yukawa interaction in terms of quark fields of definite mass, we easily see that the interaction of neutral scalar fields with quarks is[9]

$$\mathfrak{L}_N = -[m_d\overline{d}_R d_L + m_s\overline{s}_R s_L + m_b\overline{b}_R b_L + \cdots]\varphi_1^{0*}\langle\varphi_1^0\rangle^{*-1} - [m_u\overline{u}_R u_L + m_c\overline{c}_R c_L + m_t\overline{t}_R t_L + \cdots]\varphi_2^0\langle\varphi_2^0\rangle^{-1} + \text{H.c.}, \qquad (1)$$

where L and R indicate multiplication with $\frac{1}{2}(1\pm\gamma_5)$. The part of $\mathfrak{L}_N$ involving the light quarks u, d, and s may be treated as a perturbation $\mathfrak{L}_{uds}$, while terms in $\mathfrak{L}_N$ involving c, t, b,... must be included in the unperturbed QCD Lagrangian $\mathcal{L}_0$.

Putting together SU(2)⊗ U(1) and $U(1)_{PQ}$, we see that in the limit $\mathcal{L}_{uds}\to 0$ the Lagrangian would be invariant under five independent phase transformations on $\bar{u}_R u_L$, $\bar{d}_R d_L$, $\bar{s}_R s_L$, φ_1, and φ_2, with the latter two transformations supplemented with suitable phase transformations on heavy-quark bilinears $\bar{c}_R c_L$, $\bar{b}_R b_L$, ... However, because of instanton effects, we will only have a true symmetry if we eliminate anomalies by supplementing each of these phase transformations with a suitable phase transformation on $\bar{u}_R u_L$, $\bar{d}_R d_L$, and $\bar{s}_R s_L$. There are then *four* massless neutral pseudoscalar Goldstone bosons for $\mathcal{L}_{uds}=0$, which can be taken as π^0 and η^0 plus the two bosons associated with the phase transformation on φ_1^0 and φ_2^0.

The perturbation $\mathcal{L}_{uds}$ produces a 4×4 squared-mass matrix for the four Goldstone bosons, which may be calculated by the usual methods of current algebra.[10] After diagonalization, we find a π^0 and η^0 with essentially the usual masses; a strictly massless boson that is removed by the SU(2)⊗ U(1) Higgs mechanism; and the axion, with mass[11]

$$m_a \simeq \frac{N m_\pi F_\pi}{2(m_u+m_d)^{1/2}}\left[\frac{m_u m_d m_s}{m_u m_d + m_d m_s + m_s m_u}\right]^{1/2}\frac{2^{1/4}G_F^{1/2}}{\sin 2\alpha} = (23\ \text{keV})\times N/\sin 2\alpha. \quad (2)$$

Here m_u, m_d, and m_s are the quark masses appearing in the Lagrangian, with ratios[10] $m_s/m_d=20$, $m_d/m_u=1.8$; $F_\pi \simeq 190$ MeV; N is the number of quark flavors; and α is an unknown angle defined by the relations $|\langle\varphi_1^0\rangle| = 2^{-1/4}G_F^{-1/2}\sin\alpha$ and $|\langle\varphi_2^0\rangle| = 2^{-1/4}G_F^{-1/2}\cos\alpha$.

Axion emission or absorption can take place through a mixing of a^0 with π^0 or η^0, with an amplitude of form $\xi_\pi A_\pi + \xi_\eta A_\eta$, where $A_{\pi,\eta}$ are the amplitudes for emission and absorption of a massless π^0 or η^0, and $\xi_{\pi,\eta}$ are the components of the physical axion along the bare π^0 and η^0, given[11] for $N=4$ and $m_s \gg m_{d,u}$ by

$$\xi_\pi = \xi\left[\left(\frac{3m_d - m_u}{m_d+m_u}\right)\tan\alpha - \left(\frac{3m_u-m_d}{m_u+m_d}\right)\cot\alpha\right], \quad (3)$$

$$\xi_\eta = \xi[3^{1/2}\tan\alpha + 3^{-1/2}\cot\alpha], \quad (4)$$

$$\xi = \tfrac{1}{4}\,2^{1/4}G_F^{1/2}F_\pi = 1.9\times 10^{-4}. \quad (5)$$

These mixing effects should donimate for processes involving only u, d, and s quarks, because other terms are suppressed by factors m_u or m_d or m_s. [Using (3)–(5) together with the Goldberger-Treiman relation, we see that the effect of the π^0 and η^0 poles is to convert the "current algebra" masses in Eq. (1) into constituent quark masses.] We do not know α, and so ξ_π could have any value; where numerical estimates are needed we will take $\xi_\pi \simeq \xi$. On the other hand, ξ_η has a lower bound of 2ξ, but the $\eta\bar{N}N$ coupling is considerably weaker than the $\pi^0\bar{N}N$ coupling, so that π^0-a^0 mixing should dominate in most processes. There is also a direct coupling of a^0 to heavy quarks, of the form

$$\mathcal{L}_{aq} = i2^{1/4}G_F^{1/2}a^0[m_c\bar{c}\gamma_5 c\tan\alpha + m_b\bar{b}\gamma_5 b\cot\alpha + \cdots]. \quad (6)$$

Finally, with only two doublets, either φ_1 or φ_2 would have to couple to leptons, giving the axion a coupling

$$\mathcal{L}_{al} = +i2^{1/4}G_F^{1/2}a^0[m_e\bar{e}\gamma_5 e + m_\mu\bar{\mu}\gamma_5\mu\cdots][\tan\alpha \text{ or } \cot\alpha]. \quad (7)$$

If the axion has a mass below $2m_e$, it will decay chiefly by the processes $a^0\to 2\gamma$, with a rate of order $(4N/3)^2(m_a/m_\pi)^3\xi^2$ times $\Gamma(\pi^0\to 2\gamma)$, or $\approx(10^4\ \text{MeV}^{-3}\ \text{sec}^{-3})m_a^3$. For $m_a > 2m_e$, we also have $a^0\to e^+e^-$, with a rate of order $2^{1/2}G_F m_e^2 P_e/4\pi$, or $(3\times 10^8\ \text{MeV}^{-1}\ \text{sec}^{-1})m_a$ for $m_a \gg m_e$.

Would the axion have been seen in existing experiments?[12] One can think of several possibilities:

(1) Axion exchange would introduce a term in the gyromagnetic ratio of the muon of order $G_F m_\mu^2/\pi^2 \approx 10^{-8}$, comparable to the uncertainty in present calculations[13] of g_μ.

(2) Axion exchange would produce spin-spin interactions in atoms and molecules, but even for $m_a=0$ these are weaker than corresponding magnetic interactions by factors 10^{-8} in H atoms, 10^{-6} in muonic hydrogen, 3×10^{-9} in muonium, and 10^{-5} for the pp interaction in H_2 molecules, and thus

well below current theoretical or experimental uncertainties.[14]

(3) The absence of a spike at the upper end of the pion spectrum in searches for $K^+ \to \pi^+ \nu\bar{\nu}$ gives an upper limit[15] of 1.2×10^{-6} on the ratio $(K^+ \to \pi^+ a^0)/(K^+ \to \pi^+ \pi^0)$. This is safely larger than the ratio $\xi^2 \sim 4\times10^{-8}$ expected if $K^+ \to \pi^+ a^0$ proceeds through π^0-a^0 mixing. However, the axion can also be emitted through η^0-a^0 mixing, and $K^+ \to \pi^+ \eta$ is not like $K^+ \to \pi^+\pi^0$, suppressed by the $\Delta I = \frac{1}{2}$ rule, so that the ratio $(K^+ \to \pi^+ a^0)/(K^+ \to \pi^+\pi^0)$ might be expected to be 2–3 orders of magnitude larger than ξ^2. On the other hand, $K^+ \to \pi^+\eta$ cannot occur through octet terms in the effective weak Hamiltonian, and so axion emission by a^0-η^0 mixing may also be somewhat suppressed.

(4) In accelerator neutrino experiments there is generally about one π^0 produced for each ν_μ from π^+ decay, and so the a^0/ν_μ ratio should be of order $a^0/\pi^0 \approx \xi^2$. The cross section of high-energy axions on nucleons is expected to be of order $\xi^2\sigma_{\pi N}$, so that the ratio of a^0 to ν_μ events should be of order $\xi^4\sigma_{\pi N}/\sigma_{\nu N} \approx (3\times10^{-3}\ \text{GeV})/E_\nu$. In several "beam dump" experiments[16] the number of neutrinos (with $E_\nu \approx 1$ GeV) was reduced by 2–3 orders of magnitude, and so the number of axion events should have been comparable to the number of neutrino events. It is not clear to me whether the extra events would have been noticed.

(5) Nuclear reactors are expected to emit axions at a rate of order $(v_{\text{nuc}}/c)^2\xi^2 G_{\pi N}{}^2/4\pi\alpha \approx 10^{-6}$ axion per prompt γ. There is also about one $\bar{\nu}_e$ per prompt γ, so that the axion flux in reactor neutrino experiments[17] should be about 10^{-6} the $\bar{\nu}_e$ flux, or $2\times10^7\, a/\text{cm}^2\cdot\text{sec}$. These axions can produce electron recoils by the reaction $a^0e^- \to \gamma e^-$ or $a^0 \to 2\gamma$ followed by Compton scattering but very few of these events would be mistaken for elastic $\bar{\nu}_e e^-$ scattering, because the extra photons would produce veto pulses in the scintillator of NaI annulus. However, about one-fifth of the axions would have energies above 1.5 MeV, and thus would contribute to the measured background of NaI pulses if they decayed anywhere within the 10^5-cm^3 shielded volume, or if they were absorbed in the 300 kg of NaI. The axion absorption coefficient in NaI is of the order of $2^{1/2}G_F m_e{}^2/4\pi\alpha$ times the photon absorption coefficient, or about $10^{-12}\text{cm}^2/\text{g}$, so that the axion absorption rate should be of order 10^5/day. For $m_a \gtrsim 100$ keV, axion decay also produces over 10^6 pulses/day. Both rates are much faster than the measured background[17] of -160 ± 260 pulses/day. Further, about one-tenth of the axions would be above threshold for the reaction $a^0 + d \to p + n$, with cross section of order $[4\xi^2 G_{\pi N}{}^2/4\pi\alpha(2.79+1.91)^2] \times \sigma_{M1}(\gamma + d \to p + n)$, or 5×10^{-33} cm^2. Thus with 178 kg of D_2O and an efficiency of 0.043, there should have been about 4×10^5 neutron counts/day, as compared with a measured reactor-associated rate[17] of (-2.9 ± 7.2)/day.

We see that there are already several experiments which provide evidence against the existence of axions. However, our estimates of axion production and detection rates are highly uncertain, and in particular refer to a specific model with just two scalar doublets, involving the unknown angle α. Perhaps judgment should be reserved.

The reactor evidence against axions would disappear if α took a value for which $|\xi_\pi| \ll \xi$, or if axions decayed or were absorbed so rapidly that very few reached the detector. A search for monochromatic photons from the decay $J/\psi \to a^0\gamma$ may provide a good way to look for axions,[18] which does not depend on how they couple to light quarks or leptons, or how they are absorbed or decay. We expect $\Gamma(J/\psi \to a^0\gamma)/\Gamma(J/\psi \to e^+e^-)$ to be of order $m_{J/\psi}{}^2\xi^2\Gamma(\omega^0 \to \pi^0\gamma)/m_\omega{}^2\Gamma(\omega^0 \to e^+e^-) \approx 6\times10^{-4}$.

If axions are found not to exist, it will show that there is no $U(1)_{PQ}$ symmetry, and an alternative explanation for P and T invariance will have to be found. One possibility is that one of the quark masses may be zero, so that θ can be taken to have any value we like. However, the quark masses produce a $K^0 - K^+$ mass difference[10] $(m_\pi{}^2/2m_K)(m_d - m_u)/(m_d + m_u)$, which for $m_u = 0$ or $m_d = 0$ is ±18 MeV. Electromagnetic effects are expected[19] to produce an additional contribution of only about -1 MeV, and, although this value is subject to large uncertainties,[20] it seems highly unlikely that electromagnetism could shift the K-mass difference to the observed value of $+4$ MeV.

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Avoided Crossings in Molecular-Beam Electric-Resonance Spectroscopy: The Observation of Forbidden ($\Delta K = \pm 1, \pm 2, \pm 3$) Transitions in Phosphoryl Fluoride (OPF_3)

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Normally forbidden transitions obeying the selection rules $\Delta K = \pm 1$, ± 2, and ± 3 have been observed in OPF_3 in the ground vibronic state by a new avoided-crossing technique based on the molecular-beam electric-resonance method. It is shown how this technique can be used in suitable symmetric rotors to study the K-dependent terms in the rotational Hamiltonian, the effects of centrifugal distortion on the total electric dipole moment, and the nuclear hyperfine effects off-diagonal in K.

A new avoided-crossing technique based on the molecular-beam electric-resonance (MBER) method is reported with which transitions following the selection rules $\Delta K = \pm 1$, ± 2, and ± 3 have been studied in the symmetric top phosphoryl fluoride (OPE_3) in the ground vibronic state.