interaction length. We observe no dependence of our signal on the interaction point.

One interpretation of our results is that the single muon signal comes from charm production. Assuming that the parent is the D(1865) meson decaying to $K\mu\nu$ and is produced with the same distributions we have measured for $\phi$'s (i.e., $dN/dx dp_T^2 \propto e^{-2p_T(1-|x_p|)^2}$), the observed prompt muon signal corresponds to a charm cross section of approximately 40 $\mu$b. We have taken the semileptonic branching ratio for D's to be 0.11 and used a linear $A$ dependence for the production. It should be emphasized that the cross section is very sensitive to these assumptions and the estimate above can only be taken as an indication of the approximate level of the cross section.$^3$

In conclusion, we have observed a substantial signal for single prompt muon production in high energy proton interactions. If all of this signal is due to charmed particles, a cross section level of 10–100 $\mu$b is indicated for the hadronic production of charm.

References

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**A Short Review of Axions**

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A short review of the theoretical motivations for axions, as well as their phenomenology and their present experimental status is presented.

**Theoretical Background**

The existence of nontrivial topological structures in QCD$^1$ implies that the quantum vacuum state is more complicated, being given by a superposition of an infinity of classically degenerate states$^2$:

$$|\theta> = \sum_{n=-\infty}^{\infty} e^{i n \theta} |n>$$

(1)

The arbitrary parameter $\theta$, associated with the vacuum state, is a new parameter in QCD. It can be shown that the $\theta$-vacua are equivalent to including an additional term in the QCD Lagrangian of the form$^3$:

$$\mathcal{L}_0 = \theta (g^2/32\pi^2) F_{\mu
u} F^{\mu\nu}$$

(2)

Such a term is known to be a total derivative.$^4$ However, because of the topologically nontrivial structure of QCD it cannot be neglected.$^5$ Clearly, unless $\theta = 0$ (or $\theta = \pi$) this term will induce strong $P$ and $T$, and therefore $CP$, violations. This is not the only possible source of $CP$ violations in the strong interactions. When the effects of the weak interactions are included the quark mass matrix, $M$, is in general not real. Thus the condition which is necessary for strong $CP$ conservation is that

$$\bar{\theta} = \theta + \text{Arg det } M = 0$$

(3)

(Actually, as Baluni$^6$ has argued recently, the
present bound on the neutron dipole moment only requires $\bar{\theta} \leq 10^{-8}$.) We should note that, because of the topological structure of QCD, Weinberg's original argument for removing CP violations associated with the phase of the quark mass matrix is no longer valid. Although a chiral rotation can change Arg det $M$ it also changes $\theta$, because of the Adler–Bell–Jackiw anomaly, in such a way that $\bar{\theta}$ remains fixed.

One can remove the threat of strong CP violations if the theory possesses an overall chiral U(1) symmetry. Then $\theta$ can be rotated to zero. Two possibilities can be envisaged for such an automatic strong CP conserving theory:

1. The chiral symmetry obtains because one of the quarks—presumably the $u$ quark—has zero mass
2. The chiral U(1) symmetry is imposed by enlarging the weak symmetry group $G$ to $G \times U(1)_{chiral}$

The first possibility appears to be ruled out by standard current algebra arguments. However, there is still a bit of controversy on this matter.

The second possibility, which was the one advocated in ref. 8, was shown by Weinberg and Wilczek to imply the existence of a very light pseudoscalar boson—the axion.

**Phenomenology of Axions**

I shall briefly describe the phenomenological properties of axions in the standard SU(2) $\times$ U(1) model of the weak interactions in which fermions are in left-handed doublets and right-handed singlets and all Higgs multiplets are SU(2) doublets. If these conditions are relaxed, one can alter some of the properties of axions in ways which could make them even more elusive. By including two Higgs doublets and suitably restricting their interactions one can enlarge the standard model to be SU(2) $\times$ U(1),$\times U(1)_{chiral}$ symmetric. Upon spontaneous breakdown an additional pseudo-Goldstone boson appears which is associated with the extra chiral U(1) current:

$$J_3^a = f \hat{\partial} \phi + (x/2) \sum_i \hat{\tau}_i \hat{\tau}_i^a \hat{p}_i + (1/2x) \sum_i \hat{p}_i \hat{p}_i \hat{d}_i + l_i \hat{l}_i$$

Here $\phi$ is the axion field, $p_i$ are charge 2/3 quark fields, $n_i$ are charge $-1/3$ quark fields and $l_i$ are charge $-1$ lepton fields. The parameter $f$ is related to the Fermi constant:

$$f = (\sqrt{2} G)^{-1/2} \simeq 250 \text{ GeV}$$

while $x$—which is related to the ratio of Higgs expectation values—is a free parameter of the theory and is presumably of O(1).

The axion would be a real zero mass Goldstone boson were it not for the fact that $J_3^a$ has an anomaly. Its mass and its principal properties can be derived by constructing an anomaly free current which is soft—that is a current whose divergence vanishes when $m_u$ and/or $m_d$ vanishes. One finds

$$m_a = m_z f N \left( x + \frac{1}{x} \right) \frac{Z^{1/2}}{1 + Z} \simeq 25N (x + \frac{1}{x}) \text{ keV}$$

and

$$\tau_{a \rightarrow \gamma \gamma} \simeq 0.8(100 \text{ keV}/m_a)^3 \text{ sec}$$

Here $N$ is the number of quark doublets and $Z = m_d/m_u \approx 0.56.$ We should note that if $m_a > 1 \text{ MeV}$ the axion could also decay into $e^+e^-$ pairs with a lifetime of the order of $10^{-8} - 10^{-9}$ sec. Using standard current algebra methods one can also determine the coupling of axions to nucleons and leptons. One finds

$$\left. \varphi \right|_{\text{axion}} = \frac{1}{2} (f / f_a) g_{a \pi} \simeq 2 \times 10^{-10} g_{a \pi} \text{ GeV}$$

**Experimental Test of Axions**

I shall discuss three different experimental tests for axions:

1. **Decays**

The process $K \rightarrow \pi a$ has been analyzed theoretically by a number of authors and compared to the experimental bound coming from the search for the process $K^+ \rightarrow \pi^+ \nu \bar{\nu}$:

$$\Gamma(K^+ \rightarrow \pi^+ a) / \Gamma(K^+ \rightarrow \text{all}) < 2.7 \times 10^{-7}$$
Unfortunately, the theoretical estimates are quite model dependent, yielding branching ratios ranging from $10^{-5}$ to $10^{-1}$, and thus are not immediately useful. Wilczek has suggested looking for axions in $\phi$ decays. He computes

$$\Gamma(\phi \to \gamma^\prime) \sim \frac{G}{\sqrt{2\pi\alpha}} m^2 x^2 \approx 7 \times 10^{-4} x^2$$

This should be testable shortly with forthcoming SPEAR data. In the future $\Gamma'$ decays, because of the higher mass of the $b$-quark, may provide an even more stringent test.

### (2) Reactor experiments

Axion production by nuclear reactors and their possible experimental detection in experiments carried out by Reines and collaborators, has been analyzed by Weinberg, Feinberg, Micelmacher and Pontecorvo and by our group at Stanford. The analysis is made difficult because of uncertainties in estimating the axion flux from the Savannah River reactor. Below I shall quote results based on the axion flux estimated by the Stanford group of $2 \times 10^8$ axions/cm$^2$-sec. Greater fluxes, ranging to $2 \times 10^9$ axions/cm$^2$-sec, have been estimated by other authors.

Axions could have been a source of $\gamma$ background in the 1976 experiment of Reines et al. This background is given as $(160 \pm 260)$ events/day for $E_\gamma > 1.5$ MeV and is estimated again to be zero but with a larger standard deviation $(\sim 10^3$ events/day) for all $E_\gamma$. From the process $\alpha \to 2\gamma$ we estimated a $\gamma$-background of $7 \times 10^9$ $(m_\alpha/100$ KeV)$^6$ events/day for all $E_\gamma$ and 1/5 this number for $E_\gamma > 1.5$ MeV. Additionally the process $\alpha e \to e^\gamma$ would produce $\sim 10^3/x^2$ events/day. Clearly, unless $m_\alpha \approx 100$ KeV and $x \approx 1$ the axion is in serious trouble. The 1974 experiment of Reines et al. is even more problematic. Here the process searched for $(e, d \to npe_\alpha)$ could be mimicked by deuteron disintegrations of axions with $E_\alpha > 2.2$ MeV. Experimentally the number of neutron counts is given as $(2.9 \pm 7.2)$ events/day. Axions are estimated to produce $\sim 4 \times 10^8$ events/day by the Stanford group while an even higher rate is given by Weinberg and Feinberg. This is surely very bad for axions. Two caveats ought to be mentioned, however. If the axion spectrum is suppressed with respect to the $\gamma$-spectrum at high energy the rate quoted above is reduced. Further, if the axion were essentially isoscalar ($g_\gamma \approx 0$) axion deuteron disintegration would also be dynamically suppressed.

### (3) Beam dump experiments

These experiments have been analyzed by Ellis and Gaillard and in ref. 19. Here the production and detection of axions is more amenable to direct calculation. There are four relevant experiments:

a) SLAC beam dump: The production of axions is by a bremsstrahlung process, $eZ \to eZ\alpha$, which is calculable. Axions are detectable through $\mu$-pair production—which is again calculable—or by producing hadronic showers. This latter process can be estimated to occur at a rate $(g_{eXN}/g_{eXN}) B_{\gamma^2} < 4 \times 10^{-4} B_{\gamma^2}$ times a typical $\pi^0$ induced hadronic shower, with $B_{\gamma^2}$ an unknown parameter of O(1). The analysis of ref. 19 estimates that $(5.5/\alpha^4) \mu$-pairs and $\sim 200 B_{\gamma^2}/\alpha^2$ hadronic showers should have been seen. Experimentally no $\mu$-pairs and 3 or less hadronic showers were observed. For $x \approx 1$ this implies $B_{\gamma^2} < 0.03$ which is well below expectations. (For an argument suggesting $B_{\gamma^2} \approx 10^{-3}$ see, however, ref. 21).

b) CERN beam dump experiment: Here the production and detection is hadronic, although the CDHS experiment also looked for axion induced $\mu$-pairs. The quoted numbers on the product of production times detection cross sections $(\sigma_\gamma\sigma_\gamma < 2 \times 10^{-67}$ cm$^4$) yield $B_{\gamma^2} < 0.12$ consistent with the SLAC result.

c) BNL beam dump experiment: This recent beam dump experiment gives the limit $\sigma_\gamma\sigma_\gamma < 10^{-68}$ cm$^4$ which implies $B_{\gamma^2} < 0.04$, again in agreement with the other beam dump experiments.

### Concluding Remarks

The above analyses are quite discouraging for the axion idea. However, perhaps it is well to remember that almost all the experiments discussed have quite a bit of theoretical uncertainty in their interpretation. As an example we remark that if $m_\alpha > 1$ MeV then probably the reactor bounds are irrelevant, since the axion flux would be drastically reduced by phase space arguments. (The beam
dump experiments, however, are still relevant. Now $m_a$ can be large if $x$ or $1/x$ is large. The latter is excluded by the SLAC beam dump experiment, while the former would imply a large rate for $\phi \rightarrow ay$. Thus results from this latter experiment are quite important. Equally important, perhaps, is to look for axions in theoretically clean experiments like axion production by intense low energy electron machines$^{19,21}$ and with detection through $\gamma$-decay.

In view of the quite strong evidence against axions it is obviously also useful to look for alternative theoretical solutions to the $CP$ problem, which do not rely on axions. At present, however, only some rather tentative ideas exist. Some of these ideas are discussed in Weinberg's report at this Conference$^{32}$ as well as in my report at the Singapore Conference.$^{33}$

References

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