Regge-Pomeron terms over the triple-Regge and $\rho$-$A_2$ interference terms. As in previous similar experiments,[3] our data are well described by Regge-pole contributions alone. Contributions due to other terms are either small or undistinguishable from those of pole terms.

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[1]P. D. B. Collins, *An Introduction to Regge Theory and High Energy Physics* (Cambridge Univ. Press, New York, 1977).

[2]A. Mueller, Phys. Rev. D 2, 2963 (1970); C. E. de Tar *et al.*, Phys. Rev. Lett. 26, 675 (1971); R. D. Field and G. C. Fox, Nucl. Phys. B80, 367 (1974).

[3]A. V. Barnes *et al.*, Phys. Rev. Lett. 41, 1260 (1978); R. G. Kennett, Ph.D. thesis, California Institute of Technology, 1979 (unpublished), California Institute of Technology Report No. CALT-68-742, 1979.

[4]A. Borg *et al.*, Nuovo Cimento 22A, 559 (1974); J. V. Beaupre *et al.*, Nucl. Phys. B30, 381 (1971); E. Simopovlov *et al.*, Nucl. Phys. B96, 413 (1975); A. Blokzijl *et al.*, Nucl. Phys. B39, 141 (1972); P. Bosetti *et al.*, Nucl. Phys. B60, 307 (1973); M. Deutschland *et al.*, Nucl. Phys. B70, 189 (1974); C. Cochet *et al.*, Nucl. Phys. B124, 61 (1977).

[5]P. Chiliapnikov *et al.*, Phys. Lett. 35B, 581 (1971); A. Vayaki *et al.*, Nucl. Phys. B58, 178 (1973); K. Paler *et al.*, Phys. Lett. 43B, 437 (1973); P. Belliere *et al.*, Nucl. Phys. B90, 20 (1975).

[6]R. E. Pitt, Ph.D. thesis, University of California, San Diego, 1980 (unpublished).

[7]V. Barger and D. Cline, Phys. Rev. 156, 1522 (1967).

## Coherent Conversion of Very Light Pseudoscalar Bosons

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We discuss coherent conversion of hypothetical very light pseudoscalar bosons into a photon in the Coulomb and vector meson fields of a nucleus. The process provides a way to look for such bosons independently of whether their mass and lifetime allow for detection of the two-photon decay.

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In the context of spontaneously broken symmetries,[1,2] the search for the possible existence of very light pseudoscalar bosons is of continuing interest. The axion[3,4-6] is a particular example. Decay into an electron-positron pair seems to be experimentally excluded[7]; therefore we are considering masses below 1 MeV for which only detection via the decay into two photons remains a possibility. However, if the mass of the hypothetical boson is sufficiently small ($\lesssim 10$ keV), it becomes increasingly difficult to observe the two-photon decay with typical[8] experimental decay paths of a few meters because of the greatly increased lifetime. Fortunately, there is one other process which could allow for the detection of arbitrarily light pseudoscalar bosons and which is a direct consequence of the existence of the two-photon decay. This is the conversion of the boson (denoted by $a^0$) into a single photon by coherent interaction with a nucleus. The coherent interaction will be with the charge of the nucleus via exchange of a photon (the Primakoff effect[9]) and also with the total nucleon number via exchange of a strongly interacting, isoscalar vector meson, such as the $\omega^0$. In this note, we calculate this process for a current experimental situation. The coherent nuclear process is more important than Compton scattering of $a^0$ from individual electrons[3,6] and we show that, even for a low flux of $a^0$ relative to neutrinos (say[6] $10^{-7}$– $10^{-8}$) this process would give rise to events that could look like neutrino-electron scattering at high energies. Thus measurements of the latter, which is theoretically predictable in the standard model, can limit (or detect) the presence of $a^0$, which would undergo coherent nuclear conversion into a photon.

The cross section for the coherent process depends essentially upon the basic strength of $a^0$ couplings, not upon the lifetime (or mass). The usual gauge-invariant effective Lagrangian involves a parameter with dimension of length; we take this as the phenomenological semiweak coupling $2^{1/4}\sqrt{G_F} \cong 3.8\times 10^{-3} m_N^{-1}$, where $m_N$ is the nucleon mass. With $e^2 = 4\pi\alpha \cong 0.092$, the phenomenological interaction giving $a^0 \to 2\gamma$ is then

$$C 2^{1/4} G_F^{1/2} e^2 \epsilon_{\mu\nu\sigma\rho} F_\gamma^{\mu\nu} F_\gamma^{\sigma\rho} \varphi_a , \tag{1}$$

where $C$ is a number, $F_\gamma^{\mu\nu}$ is the photon-field tensor, and $\varphi_a$ is the boson field. In axion theory,[4] the decay occurs via a triangle-type virtual loop to which the axion couples with a strength proportional to the mass of the loop particle (i.e., $m_f\sqrt{G_F}$ for a fermion). The integration over virtual momenta in the loop gives a number of the order of $[4\pi/(2\pi)^3] m_f^{-1}$, leading to the effective coupling in Eq. (1) with $C\sqrt{G_F} = G_F^{1/2}/2\pi^2 \cong 1.6 \times 10^{-4} m_N^{-1}$. Guided by axion theory, we use in the following calculations this coupling strength multiplied by a number $\lambda$ which is assumed now to be of order unity. However, it should be noted that the same effective coupling strength could arise in another way; that is, a light pseudoscalar couples to the nucleon with about $10^{-5}$ of the pion-nucleon coupling $G_{\pi N}$, $G_{\pi N}^2/4\pi \cong 14.5$. The $a^0$ lifetime $\tau_a$ is given in terms of the mass $m_a$ and $\lambda$ by[10]

$$\tau_a^{-1} = \sqrt{2} m_a^3 \lambda^2 G_F \alpha^2/\pi^3 \tag{2}$$

or

$$\lambda^2 = 3.4\times 10^{-14}/\tau_a m_a^3, \tag{3}$$

with $\tau_a$ in sec and $m_a$ in GeV. We have $\lambda^2 \to 1$ for $m_a = 300$ keV and $\tau_a \cong 10^{-3}$ sec, which are typical values for the hypothetical axion,[3,4] in particular. However, for $m_a \ll 100$ keV and the scale of the semiweak coupling essentially fixed (i.e., $\lambda^2 \sim 1$), the lifetime rapidly lengthens and the probability of decay in typical experimental decay lengths,[8] which is proportional to the Lorentz-dilated inverse lifetime, that is, $m_a^4$, rapidly decreases. The coherent nuclear conversion processes into a photon, in the Coulomb field and via $\omega^0$ exchange, shown in Figs. 1(a) and 1(b), respectively, involve the effective coupling strengths $\lambda G_F^{1/2} e^2/2\pi^2$ and $\lambda G_F^{1/2} e g_\omega/2\pi^2$. For the $\omega^0$-exchange process, coherent with all $A$ nucleons, we have replaced one power of charge $e$ by $g_\omega$. We estimate $g_\omega \sim \frac{1}{3} g_{\omega NN}$, where $g_{\omega NN}^2/4\pi \cong 20$ is the empirical[11] strong $\omega^0$ coupling to nucleons. Application of an identical substitution in the empirical amplitude for $\pi^0 \to 2\gamma$ gives a branching ratio for $\omega^0 \to \pi^0\gamma$ of about 3%, as compared to the empirical value of ~9%. Thus this valence-quark model for $g_\omega$ (i.e., $\frac{1}{3} g_{\omega NN}$) seems to be a conservative estimate. Calculation of the coherent processes in Figs. 1(a) and 1(b), with neglect of nuclear recoil kinetic energy and nuclear excitation (which is suppressed by lack of coherence or by small coherent nuclear matrix elements), gives the laboratory differential cross section for $a^0$ of momentum $p$ (neglecting $m_a$) on a nucleus of charge $Z$,

$$\frac{d\sigma}{d(\cos\theta)} = \lambda^2 (1.4\times 10^{-34}\ \text{cm}^2) \left[ \frac{(Z\alpha)^2}{4} \frac{1+\cos\theta}{1-\cos\theta} + A^2 \frac{1}{9} \left( \frac{g_{\omega NN}^2}{4\pi} \right)^2 \left( \frac{p^2}{4p^2 \sin^2\frac{1}{2}\theta + m_\omega^2} \right)^2 \sin^2\theta \right.$$
$$\left. \pm 2(Z\alpha) A \frac{1}{3} \frac{g_{\omega NN}^2}{4\pi} \frac{p^2}{4p^2 \sin^2\frac{1}{2}\theta + m_\omega^2} \cos^2\tfrac{1}{2}\theta \right] \exp[-\tfrac{1}{3}(2pR_A \sin\tfrac{1}{2}\theta)^2]. \tag{4}$$

In Eq. (4), $m_\omega$ is the $\omega^0$ mass of ~0.78 GeV, $R_A \cong 1.2 A^{1/3}$ fm is the rms nuclear radius, and $\lambda^2$ is given in Eq. (3). The last (exponential) factor represents the nuclear momentum-space form factor under the simplifying assumption of a Gaussian spatial distribution of nucleons. This is adequate for our purposes because we shall be interested in detectable events that look like $\nu_\mu$-$(\bar\nu_\mu$-$)$ $e$ scattering, which at high energies is predominantly within a few degrees, i.e., $pR_A\theta \lesssim 1$.

The first term in Eq. (4) arises from the Primakoff effect, conversion in the coherent nuclear Coulomb field, and with neglect of $m_a$ is valid for $\theta \gtrsim m_a^2/2p^2$. The second term comes from $\omega^0$ exchange, and the third term is the $\gamma$-$\omega^0$ interference whose sign (constructive or destructive) is ambiguous.

We note some general features of the coherent conversion: (1) The photon spectrum in the lab-

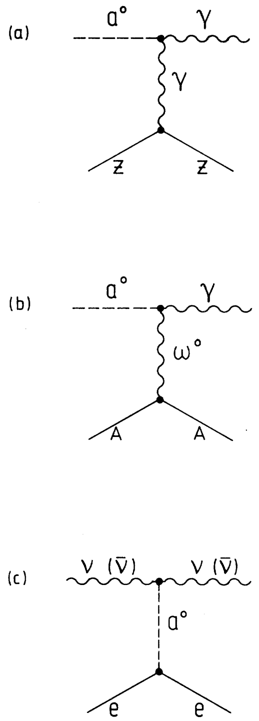


FIG. 1. Coherent nuclear conversion, $a^0 \rightarrow \gamma$. (a) Primakoff effect, (b) exchange of a hadronic vector meson, and (c) exchange of $a^0$ leading to $\nu_\mu$- ($\bar{\nu}_\mu$-) $e$ scattering.

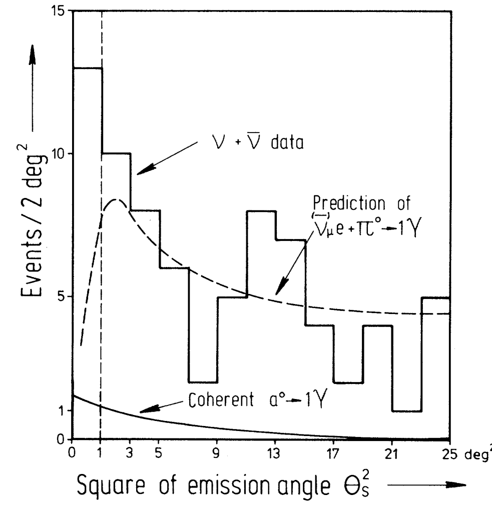


FIG. 2. Experimental results (histogram) from the experiment of Faissner *et al.* (Ref. 12) to measure $\nu_\mu$- ($\bar{\nu}_\mu$-) $e$ scattering. The dashed curve is the total expected $[(\nu_\mu + \bar{\nu}_\mu)e$ scattering and $\pi^0 \rightarrow 2\gamma]$. The solid curve represents coherent nuclear conversion, $a^0 \rightarrow \gamma$, calculated from Eq. (4) with (+) and the normalization $\lambda^2 = 1$, after folding with the hypothetical-$a^0$ energy spectrum from the Be neutrino target. About three events are contained in $\theta_s \leq 5°$.

oratory is essentially that of the incident $a^0$ modulated by the energy-dependent cross section in Eq. (4). (2) Because of the long-range Coulomb field, the Primakoff effect is strongly peaked very forward ($\theta \sim m_a^2/2p^2$) with increasing energy, with the peak cross section growing as $\sim p^4$. (3) For $a^0$ of a few MeV from a reactor, the cross section (for $\theta > 10^{-3}$) on NaI ($Z = 53$ for I) is of the order of $10^{-34}$ cm$^2$ per nucleus, which is about fifty times the maximum cross section[6] for the Compton effect on an electron (assuming that $a^0$ couples to the electron mass); the latter falls with energy (as $\sim 1/p$) above a few MeV. (4) The coherent $\omega^0$-exchange process is negligible at low energy, but the cross section grows strongly with energy up to $p \sim R_A^{-1}$, reaching a value of the order of $10^{-35}$ cm$^2$ within the diffraction peak ($pR_A\theta \lesssim 1$) on Al, for example. Since the single photon looks like a recoil electron in counter and in spark-chamber experiments[12] with $\nu_\mu$ of a few GeV, events of coherent conversion $a^0 \rightarrow \gamma$ arising from the presence of $a^0$ in the neutrino beam could measurably contaminate $\nu_\mu e$ scattering in the near-forward direction, the cross section for the latter being of the order of $10^{-42}$ cm$^2$.

To illustrate this we have taken the conditions of the experiment of Faissner *et al.*,[12] folding the hypothetical-$a^0$ energy spectrum with Eq. (4). The $a^0$ energy spectrum is assumed to follow that obtained from the measured (above 4 GeV) $\pi^\pm$ spectra for 26-GeV proton-nucleus collisions, with an extrapolation[7] below 4 GeV. The target is Al. The result is shown in Fig. 2 for an $a^0$ flux relative to neutrinos plus antineutrinos of[6] $1.4\times 10^{-7}$. It should be noted that the processes in Figs. 1(a) and 1(b) imply that $a^0$ must at the very least be produced in secondary interactions by photons from $\pi^0$ decay with something of the order of $10^{-9}$–$10^{-10}$ of the $\pi^0$ production rate. In the first experimental bin with a shower angle $\theta_s < 1°$, the coherent nuclear process produces 1.3 events, whereas $5 \pm 0.5$ events are expected[13] from $\nu_\mu e$ and $\bar{\nu}_\mu e$ scattering together (about 2 events) and from the dominant background of $\pi^0 \rightarrow 2\gamma$. With the axion spectrum we use here, the angular distribution of coherent conversion alone does not explain the data of Faissner *et al.*[12] Further, the $\nu_\mu e$ analysis involved different cuts,[12] and will be repeated taking possible axion effects into account.[13] In heavier target material the coherent nuclear process would give further-enhanced event rates relative to neutrino-electron scattering because, although the density of nuclei is reduced from that of electrons by $1/Z$, the coherent cross sections go as $Z^2$ (Primakoff effect) or $A^2$, in the near-forward direction. Other processes which produce hard photons in association with neutral-current neutrino-hadron scattering have been discussed.[14] These can give rise to a further background at the level of neutrino-electron scattering.[12] However, as (at least) three-particle final states, the energy spectrum of the photons is not that of the incident beam, and the extreme forward concentration, characteristic of the Primakoff effect in particular, is absent. An excess of apparent $\nu_\mu$- ($\bar{\nu}_\mu$-) $e$ scattering at the smallest angles would thus be expected from the presence of $a^0$ in the beam, which undergo coherent nuclear scattering into photons in the target. This is independent of whether the mass and lifetime and decay path are such as to allow detection of the $2\gamma$ decay.[15]

The process discussed here seems to allow for the direct search in current experiments for arbitrarily light pseudoscalar bosons which have something like a semiweak coupling strength. It is amusing to note that if such light objects exist and couple to the mass of fermions, and if neutrinos have finite masses, then exchange of $a^0$ will give rise to neutrino- (and antineutrino-) electron scattering [Fig. 1(c)] with a laboratory differential cross section given by

$$\frac{d\sigma^{a^0}(\nu_e \text{ or } \bar{\nu}_e)}{dy} \cong \frac{G_F{}^2 m_e p}{16\pi}\left(\frac{m_\nu}{p}\right)^2\left(\frac{2m_e p y}{2m_e p y + m_a{}^2}\right)^2, \tag{5}$$

where $m_\nu$ and $m_e$ are the neutrino and electron masses, and $y = T_e/p$ with $T_e$ the recoil electron kinetic energy. Of course, the neutrino helicity is flipped from left to right. In addition, the final-state neutrino is in general flavor mixed. If a single mass is much larger than others, it is this mass times a function of mixing angles which appears and the final-state neutrino is the flavor mixture appropriate to this mass eigenstate. However, even for low-energy neutrinos ($p \sim$ a few MeV) and near $y_{\max} = (1 + m_e/2p)^{-1}$, the ratio of this cross section to the standard ones arising from intermediate-vector-boson exchange is of order $(m_\nu/p)^2$ and hence negligible for $m_\nu \ll 100$ keV.

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[1] Y. Nambu and G. Jona-Lasinio, Phys. Rev. 124, 246 (1961).
[2] J. Goldstone, Nuovo Cimento 19, 154 (1961).
[3] S. Weinberg, Phys. Rev. Lett. 40, 223 (1978).
[4] F. Wilczek, Phys. Rev. Lett. 40, 279 (1978).
[5] R. D. Peccei and H. R. Quinn, Phys. Rev. D 16, 1791 (1977).
[6] T. W. Donnelly *et al.*, Phys. Rev. D 18, 1607 (1978).
[7] H. Faissner *et al.*, Phys. Lett. 96B, 201 (1980).
[8] F. Reines, H. S. Gurr, and H. W. Sobel, Phys. Rev. Lett. 37, 315 (1976).
[9] H. Primakoff, Phys. Rev. 81, 899 (1951).
[10] This is essentially the same as the formula in Refs. 3 and 4. See also W. A. Bardeen and S.-H. H. Tye, Phys. Lett. 74B, 229 (1978).
[11] K. Erkelenz, Phys. Rep. 13C, 194 (1974).
[12] H. Faissner *et al.* (Aachen-Padua collaboration), Phys. Rev. Lett. 41, 213 (1978).
[13] H. Faissner, in Proceedings of the International Conference on Neutrino Physics and Astrophysics: Neutrino-80, Erice, Italy, 23–27 June 1980 (to be published); H. Faissner *et al.*, to be published.
[14] E. A. Choban and V. M. Shekhter, Yad. Fiz. 26, 1064 (1977) [Sov. J. Nucl. Phys. 26, 563 (1977)].
[15] H. Faissner *et al.*, to be published.