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Laser-Induced Axion Photoproduction *

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ABSTRACT: Axion photoproduction, particularly laser and wiggler induced, is suggested as a systematic technique for probing the couplings of new elementary pseudoscalar (or scalar) particles in the MeV mass range to leptons, photons, and hadronic matter.

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The smallness of the phase θ, the measure of strong CP violation in quantum chromodynamics, is a well-known puzzle. Probably, the most elegant proposal for its solution is based on a Peccei-Quinn (PQ) symmetry,[1] a global axial symmetry explicitly broken by anomaly effects. The spontaneous breaking of a PQ symmetry naturally leads to a vanishing θ and an incumbent light pseudoscalar, the axion.[2]

The simplest implementation of the idea, in a two-doublet extension of the standard model,[3] has almost certainly been ruled out by experiment. One appealing way to evade such present experimental constraints is to increase the scale of spontaneously broken PQ symmetry from the weak scale to a much higher scale.[4] The axion is then extremely weakly coupled to ordinary matter and effectively invisible. An alternative to increasing the scale of PQ symmetry breaking is to break universality and allow a more general pattern of axion couplings to quarks and leptons.[5]

Recent results from heavy ion experiments[6] have stimulated interest in the latter possibility. Coincident electron-positron pairs have been observed with approximately equal laboratory energies: $E_{e^+} + E_{e^-} = 2m + 760$ KeV $\pm$ 20 KeV, and $E_{e^+} - E_{e^-} \simeq 0 \pm 30$ KeV in 5.83 MeV/nucleon $U + Th$ collisions at GSI (Darmstadt). Any conventional atomic or nuclear mechanism that produces an e^+e^- pair in close vicinity to the nuclear Coulomb field would lead to a significant skewing of the e^+ and e^- spectra. While the interpretation of the experiment is not uncontroversial, the results appear to be consistent with the near-threshold production and decay of a neutral particle of mass $M \sim 1.8$ MeV. It is tempting to identify such a light particle with the axion of a spontaneously broken PQ symmetry. Constraints from the electron anomalous moment[7,8] limit the coupling, $g_a a\bar{e}\gamma_5 e$ of an elementary pseudoscalar to the electron to $\alpha_a = g_a^2/4\pi \leq O(10^{-8})$, which corresponds to a lifetime of $\tau_{a\to e^+e^-} = \left[\alpha_a(1-4m^2/M^2)^{\frac{1}{2}}M\right]^{-1} \geq O(10^{-13})$ sec. Previous searches for the axion were limited to particles with lifetimes of 10^{-11} sec. or longer. These include beam dump experiments[9] and the decays $K^+ \to \pi^+ a$,[10] $J/\psi \to \gamma a$,[11] and $\Upsilon \to \gamma a$[12] which will have to be reanalyzed with sensitivity to low invariant mass e^+e^- pairs. Therefore, a rather narrow window apparently exists for a light, neutral particle with a lifetime between 10^{-13} and 10^{-11} sec. Because of the breakdown of universality in the alternative class of models, the absence of an axion signal in experiments involving heavy quarks or constraints from $g-2$ of the muon may not be definitive.

In this note we propose axion photoproduction on electrons ($\gamma e \to ae$) and other targets as a technique to observe the axion and systematically identify its various couplings. Even if the axion interpretation of the heavy ion experiment turns out to be incorrect, we regard this proposal as a general technique to search for such a weakly interacting particle of any spin-parity in the MeV mass range. Since there are three contributing diagrams in Fig. 1, photoproduction is sensitive not only to the axion-fermion couplings but also to its anomaly-driven two-photon coupling $\kappa a F_{\mu\nu}\tilde{F}^{\mu\nu}$ through the t-channel graph.[13] In particular we have in mind a laser/wiggler type of configuration where a low energy photon collides with a relativistic electron beam.

The advantages of this class of experiments are striking:

(i) Because of high laser/wiggler luminosity, the rates are high.

(ii) The axion is produced at high energy; since it is weakly interacting it travels a considerable distance before decaying. This allows shielding to eliminate electromagnetic backgrounds for a neutral particle of sufficiently long lifetime, $\tau \geq 10^{-13}$ sec.

(iii) The process is very clean theoretically; the kinematics can be tuned to determine the various couplings of the graphs in Fig. 1. The key observables are the total energy and energy fraction of the axion. At low energies, where s is not too far above threshold the s and u channel poles dominate, and the axion coupling to electrons α_a can be determined. At high energies (and fixed t), this part of the total cross section falls like $\frac{1}{s}$ so the t-channel graph dominates, allowing the two-photon coupling to be determined. However, κ contains a natural factor of α in its definition and consequently is expected to be quite small.[13] We present detailed estimates below.

Although the photoproduction cross-sections for pions were calculated long ago in the days of pion-nucleon physics,[14] we give here complete formulae including interference terms appropriate for axion photoproduction. We also give some corresponding results for scalar photoproduction for comparison. In a frame where the incident photon and electron are collinear

$$\begin{aligned} s - m^2 &= 2k \cdot p = 2\omega(p^0 + p^z) = 2\omega p^+ \\ t - M^2 &= -2k \cdot q = -2\omega q^+ = -2\omega p^+ x \end{aligned} \tag{1}$$

where k, q and p are the four-momenta of the photon, axion and incident electron respectively, ω is the photon energy, and $x = \frac{q^0+q^z}{p^0+p^z}$ is the fractional light cone momentum of the axion ($0 < x < 1$). The differential cross-section for pseudoscalars is

$$\begin{aligned} \frac{d\sigma}{dx} = \frac{\pi\alpha\alpha_a}{s-m^2}\Bigg\{ \frac{x}{1-x}\Bigg[&-\frac{2\tilde{M}^2}{(s-m^2)^2}\left(s - \frac{m^2}{1-x} - \frac{M^2}{x}\right) + x \\ &+ 2\gamma x^2 \frac{(s-m^2)}{x(s-m^2)-M^2} \Bigg] \\ &+ \frac{\gamma^2}{m^2}\frac{(s-m^2)^2}{x(s-m^2)-M^2}\left[1 + (1-x)^2 - \frac{2x^2m^2}{x(s-m^2)-M^2}\right]\Bigg\} \end{aligned} \tag{2}$$

where $\gamma = \frac{\kappa m}{g_a}$ and $\tilde{M}^2 = M^2$. For the scalar case, $\tilde{M}^2 = M^2 - 4m^2$ and $\gamma \to 0$. (We assume the two-photon coupling to scalars is negligible.)

One can draw a number of conclusions from Eq. (2). For low values of s and γ not too large, the terms independent of γ dominate the cross section (cf. Figs. 1a–1b). The total cross section for $\gamma = 0$ is shown in Fig. 2 as a function of s. The

differential cross section is plotted in Fig. 3 for various s and $\gamma = 0$. Sufficiently accurate measurement of $\frac{d\sigma}{dx}$ would allow discrimination of the pseudoscalar case from the scalar case. If γ is large relative to expectations, the contribution of the t-channel graph might be measurable even at low s. This is illustrated by the dashed curve in Fig. 3.

For s well above threshold the total cross section approaches

$$\sigma_{\gamma e \to ae} \cong \pi\alpha\,\alpha_a \left\{ \frac{1}{s}\left(\ell n\frac{s}{m^2} - \frac{3}{2}\right)(1 + 2\gamma) + \frac{2\gamma^2}{m^2}\ell n\frac{s^3}{m^2M^4} \right\} \tag{3}$$

At fixed t and large s ($x \to 0$), the pure t-channel graph dominates (as long as the two-photon coupling remains pointlike.) The differential cross section is approximately

$$\frac{d\sigma}{dx} \cong \frac{2\pi\alpha\,\alpha_a\gamma^2}{m^2}\frac{s}{-t} = \frac{2\pi\alpha\alpha_a\gamma^2}{m^2}\frac{s}{x(s-m^2)-M^2} \tag{4}$$

in this limit.

The particular experiments we have in mind are the following: laser/wiggler generated photons on a relativistic electron beam. Typical energies for threshold $\gamma + e \to a + e$ production are:

a)	$\omega = 4.5$ eV	$E_e = 300$ GeV	(FNAL, SPS)
b)	$\omega = 27$ eV	$E_e = 50$ GeV	(SLC, LEP)
c)	$\omega = 92$ eV	$E_e = 14.5$ GeV	(PEP, PETRA)

(a) can be accomplished with an optical laser; (b) and (c) can be achieved with wigglers[15] directed onto an electron beam. The basic experimental configuration is similar to that used to obtain a monoenergetic photon beam by the back-scattered Compton effect. The axion is emitted along the incident electron direction with a finite fracton of the electron beam energy $x \lesssim 1$. Since the axion is relativistic, its laboratory decay length is long enough ($d = \gamma\tau_a = \frac{E_a}{M}\tau_a \sim 0.7$ meters for $E_a = 100$ GeV and $\tau_a \sim 4 \times 10^{-13}$ sec.) for it to be identified by its penetration through matter and subsequent decay.

In experiments (b) and (c) one can utilize the UV photons produced by a wiggler in one stored beam to interact with the other beam. We proceed with some remarks on counting rates. The axion production cross-section is 10^{-6} of the background Compton scattering. The laser/wiggler intensity is such that 10% or more of the electrons in a stored or incident electron beam can be converted to photons. Therefore at least 10^{-7} of the electrons can be converted to axions, providing a relativistic *beam of axions* of 10^3/sec to 10^5/sec, which should be sufficient to study the axion's properties mentioned here. It is also conceivable to investigate the relativistic axion's elastic and inelastic interactions with matter. This could include diffractive processes, interactions with strong external electromagnetic fields, and production of new particles.

Other possible experimental scenarios are

$$\text{i)}\quad \gamma e_b \to a e_b$$
$$\text{ii)}\quad eZ \to eZa$$

where in (i) e_b is a bound electron and γ is a high energy photon beam; (ii) is the Primakoff process in the Coulomb field of a nucleus.[16] The first process is feasible if the e^+e^- pair from the axion can be identified and distinguished from the electromagnetic background. The axion is produced in the forward direction, emphasizing the t-channel graph of Fig. 1c. Hence the two photon coupling can be determined.

In the Primakoff process (ii) an incident electron scatters coherently off the nuclear Coulomb field and emits an axion. The electron differential cross section is given approximately by

$$\frac{d\sigma_{eZ\to eZa}}{d\hat{s}} \sim \frac{2\alpha}{\pi} Z^2 \, \ell n(\hat{s}R^2) \frac{\sigma_{\gamma e\to ae}(\hat{s})}{\hat{s}} \quad (5)$$

where R is the atomic size of the target and $\hat{s}$ is the center of mass energy squared of the subprocess $\gamma e \to ae$. Since $Z^2\alpha \sim 1$, this process is very efficient in converting the cross-section for incident photons into the cross section for incident electrons. The latter remark should be relevant to the beam dump experiments.[9] Thus, these experiments are dependent upon the lifetime and energy cuts as opposed to being rate limited.

In conclusion, we have presented a useful list of experiments that are interesting for observing an axion in the MeV mass range and setting limits on its coupling to electrons and photons. Qualitatively similar results to those presented here hold for a weakly interacting scalar and other spin-parity particles in the same mass range. Photoproduction experiments can also be carried out with other stored beams or targets $(\mu, p, \pi, K\ldots)$ to systematically probe the axion's couplings to other particles and constituents.

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$$\Delta a_e = -\frac{\alpha_a}{2\pi}\int_0^1 dz \frac{z^3}{z^2 + (1-z)M^2/m_e^2}.$$

Since $|a_{EXP} - a_{\rm QED}| < 2 \times 10^{-10}$ (see P.B. Schwinberg, *Phys. Rev. Lett.* **47**, 1679 (1981), and T. Kinoshita, *Phys. Rev. Lett.* **47**, 1573 (1981)), this implies $\alpha_a \leq 10^{-8}$.

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FIGURE CAPTIONS

Figure 1: The three Feynman diagrams which give the amplitude for photoproduction of a fundamental pseudoscalar particle (dashed line, four-momentum q) which couples to electrons (solid line, incident four-momentum p).

Figure 2: The total photoproduction cross-section for a pseudoscalar particle in nanobarns, assuming $\alpha_a = g_a^2/4\pi = 10^{-8}$ and $\gamma = 0$.

Figure 3: The differential photoproduction cross-section (in MeV^{-2} units) for a pseudoscalar particle, as a function of the fractional light-cone momentum $x = (q^0 + q^z)/(p^0 + p^0)$. The three solid curves are for three different values of center of mass energy squared ($s = 6, 8, 10\ \mathrm{MeV}^2$) and $\kappa = 0$. The effect of a large $\kappa (= 0.1\ m^{-1})$ on $\frac{d\sigma}{dx}$ is illustrated by the dashed curve for $s = 6\ \mathrm{MeV}^2$.

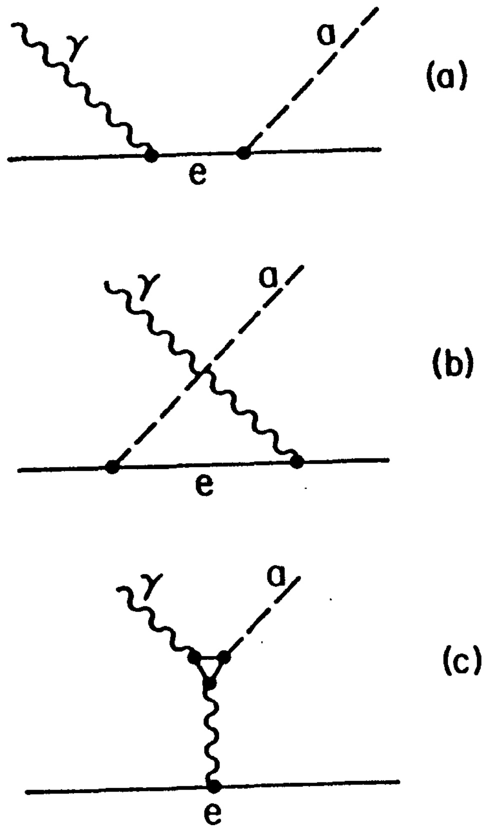

Figure 1

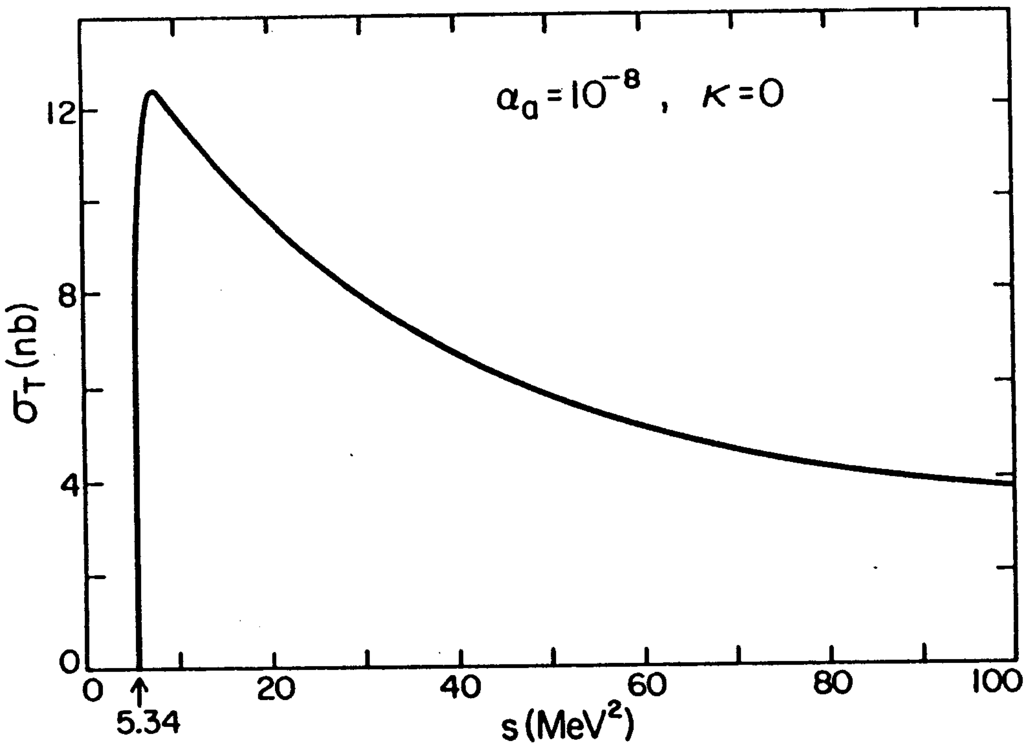

Figure 2

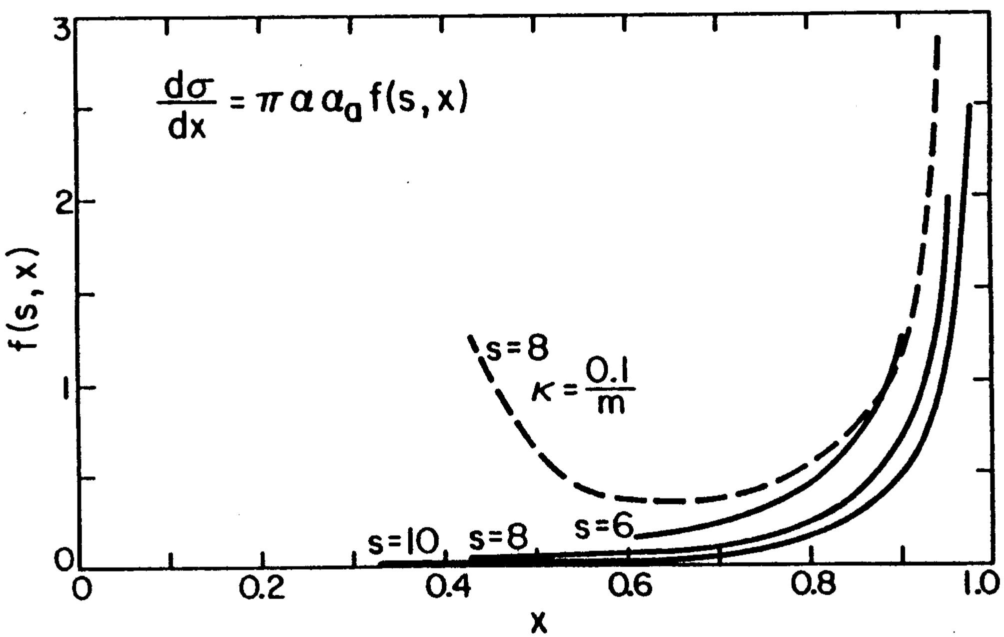

Figure 3