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THE SEARCH FOR CHARGED-LEPTON SPECIFIC FORCES AND THE PEGASYS FACILITY*

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ABSTRACT

This paper discusses the electroproduction of lepton pairs as a method of searching for a charged-lepton specific force, and as a general method of searching for deviations from conventional quantum electrodynamics. The use of the PEGASYS facility for these purposes is briefly described. Search possibilities in other energy ranges are noted.

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I. CHARGED-LEPTON SPECIFIC FORCES: CONCEPT AND MODEL

There is not only a standard model of particle physics, there is also a standard set of hypotheses and speculations. For example, proposed new particles such as the Higgs particle and the axion are assumed to couple to both leptons and quarks. In general the standard model and standard set of speculations treat similarly leptons and quarks.

But there are three facts which argue against too much similarity between leptons and quarks.

(*i*) Violation of lepton conservation has not been found, the lepton mixing angles could be exactly zero.

(*ii*) In a lepton doublet the ratio of the charged lepton mass to the neutrino mass is very large compared to the corresponding quark ratios, the lepton mass ratio may be infinite.

(*iii*) This is a force acting on quarks but not leptons, the strong force. Why not the converse?

These three facts incite the speculation that there may be a force, and a particle carrying that force, which couples only to leptons. In this talk I consider the more limited question of the existence of a force coupling only to charged leptons, for brevity called a charged-lepton specific force. Theoretical and experimental answers to this charged-lepton specific force question require a model, although as I discuss in the next section this question has raised more general considerations.

Hawkins and I[1] use a model in which the charged-lepton specific force is carried by a neutral particle called λ, with mass m_λ. We allow the λ to have $J^P = 0^+, 0^-, 1^+$, or 1^-, but emphasize the pseudoscalar and vector cases for the sake of brevity. The coupling to a charged lepton ℓ is

$$\text{pseudoscalar:} \quad -i\, g_{\lambda\ell}\, \bar{v}_\ell\, \gamma_5\, u_\ell \qquad (1a)$$

$$\text{vector:} \quad -i\, g_{\lambda\ell}\, \bar{v}_\ell\, \gamma_\mu\, u_\ell \qquad (1b)$$

We define $\alpha_{\lambda\ell} = g^2_{\lambda\ell}/4\pi$ in analogy to $\alpha = e^2/4\pi$.

The model does not constrain the dependence of $\alpha_{\lambda\ell}$ on the properties of the lepton ℓ; $\alpha_{\lambda e}$, $\alpha_{\lambda u}$, and $\alpha_{\lambda\tau}$ are independent of each other, and some may be zero. Hawkins and I[1] have limited our model to conservation of lepton number at the $\ell - \lambda - \ell$ vertex; the model can be extended to allow lepton number nonconservation.

I illustrate in Figs. 1–3 the methods for detecting λ or its effects for the case of λ coupling to the electron. Effects of a virtual λ might be de-

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tected by measurement of $g_e - 2$, Fig. 1a, by study of $e^- + e^- \to e^- + e^-$, Fig. 1b, or by study of $e^+ + e^- \to e^+ + e^-$, Fig. 1c.

If $m_\lambda > 2m_e$ a real λ might be detected in

$$\begin{gathered} e^+ + e^- \to e^+ + e^- + \lambda \\ \lambda \to e^+ + e^- \end{gathered} \tag{2}$$

as shown in Fig. 2, or in electroproduction

$$\begin{gathered} e^- + N \to e^- + N' + \lambda \\ \lambda \to e^+ + e^- \quad , \end{gathered} \tag{3}$$

Fig. 3. Here N represents the target proton or nucleus, N' represents the final hadrons.

In the processes in Eqs. 2 and 3 with $m_\lambda > 2m_e$ the λ lifetime is

$$\begin{aligned} \text{pseudoscalar:} \quad \tau_\lambda &= \frac{2\hbar}{\alpha_{\lambda e} m_\lambda} \left(1 - \frac{4m_e^2}{m_\lambda^2}\right)^{-1/2} \\ \text{vector:} \quad \tau_\lambda &= \frac{3\hbar}{\alpha_{\lambda e} m_\lambda} \left(1 - \frac{4m_e^2}{m_\lambda^2}\right)^{-1/2} \times \\ & \left(1 + \frac{2m_e^2}{m_\lambda^2}\right)^{-1} \end{aligned} \tag{4a}$$

when $m_\lambda \gg 2m_e$

$$\tau_\lambda \sim \frac{10^{-21}}{\alpha_{\lambda e} m_\lambda} \text{ sec.} \tag{4b}$$

with m_λ in MeV/c^2. In this paper I am concerned with $m_\lambda > 10$ MeV/c^2 and $\alpha_{\lambda e} > 10^{-8}$ so that λ has a short lifetime. If $m_\lambda > 2m_\ell$ with $\ell = \mu$ or τ and $\alpha_{\lambda\ell} \neq 0$ then τ_λ will be smaller and there will be an additional signal for the λ:

$$\begin{gathered} e^- + N \to e^- + N' + \lambda \\ \lambda \to \ell^+ + \ell^- \end{gathered} \tag{5}$$

The λ search proposal for the PEGASYS facility uses the electroproduction reaction in Eq. 3 and Fig. 3. The total cross section has the form

$$\sigma = \alpha_{\lambda e} \alpha^2 f(\sqrt{s}, m_\lambda) \tag{6}$$

The $\alpha_{\lambda e}$ comes from $g_{\lambda e}$ at the $e - \lambda - e$ vertex and occurs just once in σ.

Tsai[2] has made extensive calculations of this electroproduction process. Figure 4 shows his calculation of the differential cross section

$$\frac{1}{\alpha_{\lambda e}} \frac{d\sigma}{dx} \tag{7}$$

for a 14.5 GeV incident e^- on a fixed-target proton, the PEGASYS case. Here λ is a vector particle and $x = E_\lambda / E_1$ where E_λ is the λ energy and E_1 is the incident e^- energy, both in the laboratory frame. The cross section decreases rapidly as m_λ approaches its maximum value. These cross sections are 10^{-27} to 10^{-36} cm^2 for $\alpha_{\lambda e} = 1$. As discussed in Sec. IV, a search using the PEGASYS facility can probe $\alpha_{\lambda e}$ to values as small as 10^{-7} for $20 \leq m_\lambda \leq 2000$ MeV/c^2.

II. WHAT DO WE KNOW ABOUT ELECTROPRODUCTION OF LEPTON PAIRS?

The electroproduction of lepton pairs occurs through the quantum electrodynamics processes of Fig. 5. These processes have been known for many decades; these processes have been used for decades for the production of positron and muon beams; these processes are the backgrounds in many experiments including the proposed λ searches. Yet in the GeV energy range there have been no precise experiments on the electroproduction of lepton pairs.

The reason for no experimental interest has been that conventional speculation on deviations from conventional quantum electrodynamics assume the deviations would take the forms

$$\frac{1}{1 \pm s/\Lambda^2} \quad \text{or} \quad \frac{1}{1 \pm q^2/\Lambda^2} \tag{8}$$

where s and q^2 are the squares of energies and four-momentum transfers. Very high energy measurements of Bhabha scattering at e^+e^- colliders give Λ values greater than 100 GeV. The pair electroproduction measurements described in this paper involve much smaller s and q^2 values.

But suppose there is a deviation from conventional quantum electrodynamics which involves a mechanism independent of s and q^2, the λ particle model with small $\alpha_{\lambda\ell}$ for example. Then, higher energy tests are not relevant. Therefore precise studies of the processes in Fig. 5 are interesting. There are two classes of studies.

(i) One class involves the measurement of the angle, energy, and mass distributions of e^+e^- pairs and $\mu^+\mu^-$ pairs, directly examining the processes in Fig. 5.

(ii) The second class encompasses studies of the angle and energy distributions of single e^+, μ^-, and μ^+. Here one is looking for unexpected sources of charged leptons, sources outside of charged-lepton pair production. A meaningful search requires good theoretical and experimental knowledge of the expected sources such as

$$e^- + N \to e^- + \text{hadrons} \qquad (9a)$$

$$\text{hadron} \to e^+ + \nu_e + \ldots \qquad (9b)$$

or

$$\text{hadron} \to \mu^+ + \nu_\mu + \ldots \qquad (9c)$$

This second class of searches requires an apparatus such as the PEGASYS facility which allows direct studies of the hadron electroproduction process in Eq. 9a. Incidentally a decade old measurement[3] of the electroproduction of muons in a thick target is still unexplained.

III. PRESENT LIMITS ON CHARGED-LEPTON SPECIFIC FORCES

In this section I summarize the present limits on charged-lepton specific forces as found by Hawkins and me.[1] Our interest is the region $m_\lambda > 1$ MeV/c, below that mass there are limits on $\alpha_{\lambda e}$ from astrophysics which we did not discuss. However, a smaller mass range is included in Fig. 6 which gives the excluded $m_\lambda - \alpha_{\lambda\ell}$ limits from $g_e - 2$ and $g_\mu - 2$ measurements.

If λ couples only to the muon, the only other measured process which probes $\alpha_{\lambda\mu}$ is μ trident production

$$\begin{aligned} \mu^\pm + N \to \mu^\pm + N' + \lambda \\ \lambda \to \mu^+ + \mu^- \quad , \end{aligned} \qquad (10)$$

analogous to electroproduction of e^+e^- pairs in Eq. 3. T. Sloan[4] and N. Dyce[5] are looking at the limits on $\alpha_{\lambda\mu}$ which are set by the μ trident data of the European Muon Collaboration. In Ref. 1 $\alpha_{\lambda e}\alpha_{\lambda\mu}$ product limits are considered; the rest of this section is limited to $\lambda - e$ coupling.

Two kinds of electron beam dump experiments[6–13] lead to a further excluded region[1] for $m_\lambda \lesssim 15$ MeV/c^2, Fig. 7. These considerations were partly based on the work of Tsai.[14]

High energy Bhabha scattering

$$e^+ + e^- \to e^+ + e^- \qquad (11)$$

provides further limits on $\alpha_{\lambda e}$ in the larger m_λ region, Figs. 8 and 9. This is based on the $\sqrt{s} =$ 29 GeV measurement of Derrick *et al.*[15] The horizontal part of the limit curves in Figs. 8 and 9 is controlled by the interference of λ and γ exchange in the t-channel, Fig. 1c. The dip at $m_\lambda = 29$ GeV is the resonance at $m_\lambda = \sqrt{s}$ in the s-channel.

There is no practical way to increase the t-channel sensitivity, the limit is set by the uncertainty in normalizing $\sigma(e^+e^- \to e^+e^-)$. In Figs. 8 and 9 the measured ratio $\sigma(e^+e^- \to e^+e^-)/\sigma(e^+e^- \to \gamma\gamma)$ from Ref. 15 was used since $e^+ + e^- \to \gamma + \gamma$ does not depend on λ exchange in lowest order. There is no practical way to scan the $m_\lambda = \sqrt{s}$ resonance from $m_\lambda \sim 10$ MeV/c^2 up, using e^+e^- colliders, for two reasons. First, there are no e^+e^- colliders in some $\sqrt{s}$ regions, below about 500 MeV for example. Second, it would take years of scanning time to get the good sensitivity. There are a few old data sets in which some energy ranges have been scanned, at SPEAR above 3.5 GeV and at PETRA at higher energies. I have not examined what can be deduced from these old scans. The method of normalizing $\sigma(e^+e^- \to e^+e^-)$ is crucial in using such scans in a λ search; small angle Bhabha scattering from t-channel exchange or another process must be used.

Hawkins and I[16] have also looked for a λ signal using

$$\begin{aligned} e^+ + e^- \to e^+ + e^- + \lambda \\ \lambda \to e^+ + e^- \quad , \end{aligned} \qquad (12)$$

the process in Fig. 2. We used 29 GeV data obtained with the Mark II detector at PEP. The total luminosity is about 200 pb^{-1}. At equivalent $\alpha_{\lambda e}$ values in the range of 10^{-5} to 10^{-6} we see e^+e^- pairs and $\mu^+\mu^-$ pairs which could come from the conventional processes:

$$\begin{aligned} e^+ + e^- \to e^+ + e^- + \gamma_{virtual} \\ \gamma_{virtual} \to e^+ + e^- \text{ or } \mu^+ + \mu^- \end{aligned} \qquad (13)$$

as well as from an unconventional source. A factor of 100 increase is needed in the product of cross section and luminosity to get a secure measure of the background process in Eq. 13 and to search for a λ from Eq. 12 or for other unconventional sources of e^+e^- pairs. Since the cross sections for λ production, Eq. 12, and the relevant background process, Eq. 13, vary as log(s), I don't see how to obtain this factor of 100 in e^+e^- collisions.

IV. THE SEARCH USING PEGASYS

A. PEGASYS

Increasing substantially the sensitivity and solidity of searches for charged-lepton specific forces or other unconventional electroproduction processes imposes five requirements on an electroproduction experiment:

(*i*) There must be a large increase in the number of scattered electrons compared to the similar experiment discussed in III. This is needed, for example, to provide an increased source of λ's in the model of Sec. I.

(*ii*) The experiment must allow a precise measurement of the mass of e^+e^- pairs. If the decay $\lambda \rightarrow \mu^+ + \mu^-$ is to be studied, the same is true for $\mu^+\mu^-$ pairs.

(*iii*) The experiment must have a large angle and momentum acceptance so that a wide range of e^+e^- pair mass and the scattered electron can be detected.

(*iv*) The experiment must provide for very good e-hadron separation. It is important that $\pi^\pm$ and $K^\pm$ distributions also be studied so that particle misidentification backgrounds can be well understood.

(*v*) A very thin target is important to eliminate confusion from secondary processes in the target.

The PEGASYS facility,[17] shown schematically in Fig. 10, meets these requirements. It is a gas-jet, fixed-target experiment designed for the electron beam at the PEP storage ring. A major purpose of PEGASYS is to study a new, vast range[17] of nuclear and particle physics connected with the electroproduction of hadrons. Some of the major design features are:

- PEGASYS will occupy all of a straight-section, interaction region at PEP.
- PEGASYS will normally operate parasitically with both e^+e^- collision experiments and the use of PEP as a synchrotron radiation facility.
- Electron energies of 5. to 14.5 GeV will be used. For the searches discussed in this paper, the smaller energy enhances the sensitivity in the smaller m_λ range.
- The target is a cold-cluster gas target which will operate with hydrogen, deuterium, or the rare gases.
- The experiment will have a forward magnetic spectrometer with large solid angles and magnetic field perpendicular to the e^- beam. (The beam is shielded from the field by an iron plate.) The forward spectrometer has drift chambers for precise angle and momentum measurements, it has a full set of devices for $\gamma, e, \pi^\pm, K^\pm$, and p identification. The searches discussed in this paper primarily use the forward spectrometer. To study $\mu^+\mu^-$ pairs, μ detection devices will be added.
- The target will be surrounded by detection devices for large-angle and backwards γ's and hadrons, again with good angle and energy measurements.

B. Luminosity

The luminosity of the PEGASYS facility is very large, it is extraordinary for a very thin target device. The luminosity will be in the range of

$$10^{32} \lesssim L \lesssim 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \qquad (14)$$

With 10^7 s per year, cross sections as small as 10^{-39} to 10^{-40} cm^2 can be probed.

C. λ Search Method and Goals

The λ search method is illustrated in Fig. 11a. We will detect the e^+e^- pair and the scattered electron. The general background is from the process in Fig. 5. But as Tsai[18] pointed out the background reduces to the diagram in Fig. 11b when we require

$$p_\perp(\lambda) = p_\perp(\text{scattered } e^-) \qquad (15)$$

With the condition of Eq. 15 imposed, the cross section for vector λ production in Fig. 11a is equal to the cross section of conventional pair production when

$$\alpha_{\lambda e} = \frac{2}{3\pi}\,\alpha^2\,\frac{\Delta m}{m} \qquad (16)$$

where $\Delta m/m$ is the mass resolution of the e^+e^- pair. PEGASYS has $\Delta m/m$ of the order of 10^{-2} in much of the e^+e^- mass region, hence for a vector λ we can explore down to values of

$$\alpha_{\lambda e} \sim 10^{-7} \ , \ \lambda \text{ vector} \qquad (17a)$$

The luminosity, Eq. 14, is sufficient for this level to be reached in less than a year's data acquisition. If λ is a pseudoscalar particle, the λ production cross section is about 3 times smaller, hence the $\alpha_{\lambda e}$ sensitivity reaches down to about

$$\alpha_{\lambda e} \sim 3 \times 10^{-7} \ , \ \lambda \text{ pseudoscalar} \qquad (17b)$$

In a half decade of data acquisition PEGASYS will reach levels 10 times smaller than those in Eq. 17, if the $\Delta m/m$ resolution can be decreased or methods can be found to distinguish between the processes in Fig. 11.

V. OTHER MODELS, OTHER MASSES

A. Other Models

My first thoughts about λ searches were inspired by the puzzling appearance in heavy ion collisions[19] of e^+e^- pairs with mass peaks in the range of 1.5 to 1.8 MeV/c^2. Most studies of this phenomenon have assumed the existence of a neutral elementary particle like a λ with mass in that range. Indeed many of the beam dump experiments noted in Sec. III were searches for such a particle based on the calculations of Tsai[14] and of Olsen and Holvik.[20]

A speculative interpretation of the heavy ion produced e^+e^- pairs assumes they come from the decay of an extended, atom-like, object in which the e^+ and e^- are in a bound state. This requires unconventional QED or an unknown force. Such an object could be electroproduced in analogy to the electroproduction at high energies of positronium, a process discussed by Holvik and Olsen.[21] This atom-like object has a large break-up cross section[21] and might be best sought in a very thin target such as is used in PEGASYS. I have not studied the suitability of the PEGASYS forward spectrometer for such a search, the spectrometer may not encompass sufficiently small angles.

B. Other Masses

The sensitivity to $\alpha_{\lambda e}$ of the PEGASYS experiment gets radically worse as the m_λ search region approaches the threshold mass of 4.4 GeV/c^2. What is needed is higher center-of-mass energy $e^- - p$ collisions. The experiments Zeus and H1 being built for HERA offer this possibility. I think the detectors will work as designed for λ searches.

For the m_λ range above PEGASYS but below 10 GeV/c^2, a sensitive search can be done with e^+e^- collider B-Factories with proposed luminosities of

$$10^{33} \leq L \leq 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$$

The reaction

$$e^+ + e^- \to e^+ + e^- + \lambda$$
$$\lambda \to e^+ + e^- \text{ or } \mu^+ + \mu^-$$

would be used. The detectors at CESR may also have interesting data on this reaction now that the luminosity of CESR is 10^{32} cm^{-2} s^{-1}. This remark also applies to an upgraded PEP.[22].

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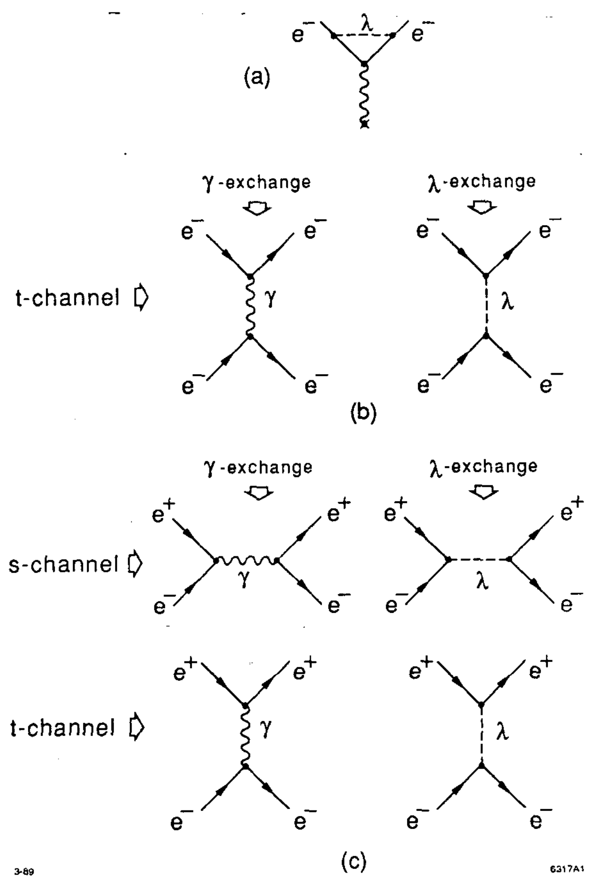

Fig. 1. Diagrams showing how a virtual λ could affect measurements of: (a) $g_e - 2$, (b) $e^- + e^- \rightarrow e^- + e^-$, and (c) $e^+ + e^- \rightarrow e^+ + e^-$.

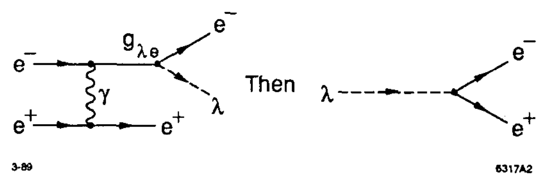

Fig. 2. Example of diagram for $e^+ + e^- \rightarrow e^+ + e^- + \lambda$. The λ then decays.

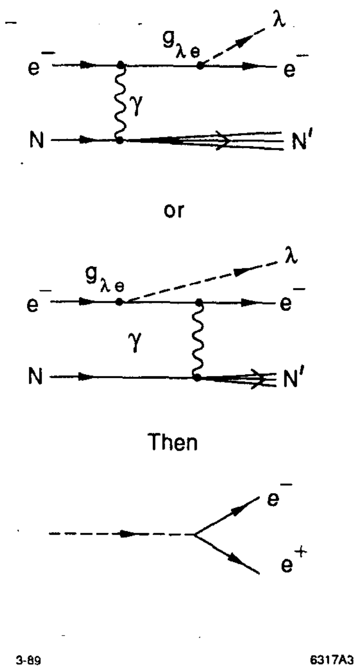

Fig. 3. Electroproduction of λ with $g_{\lambda e}$ at the $e - \lambda - e$ vertex. The λ then decays.

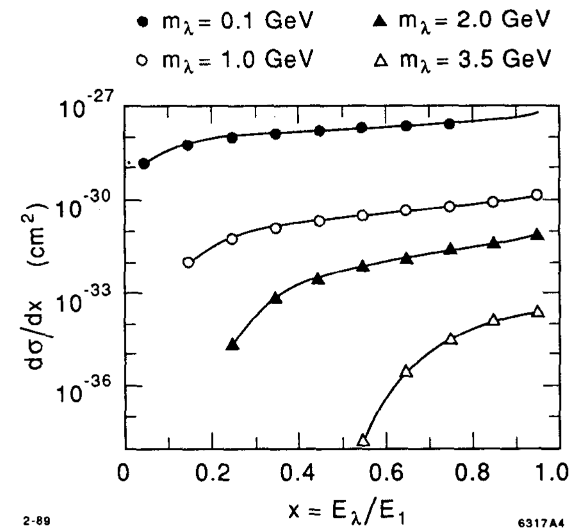

Fig. 4. The differential cross section $(1/\alpha_{\lambda e})d\sigma/dx$ for electroproduction of a vector λ on a proton at 14.5 GeV.

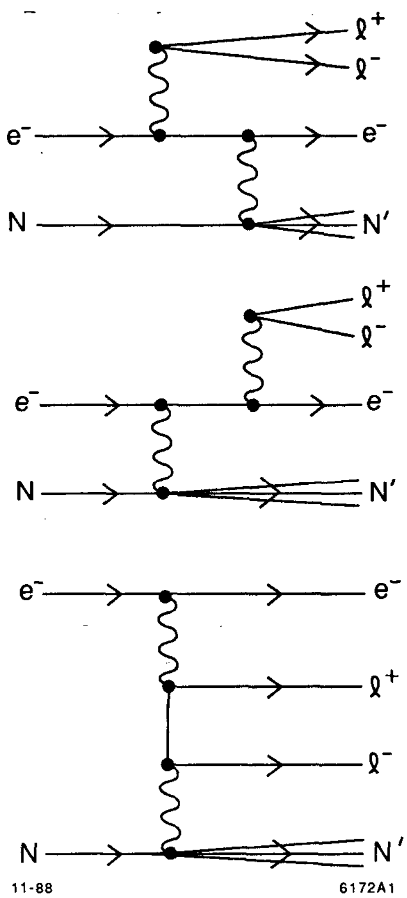

Fig. 5. Electroproduction of lepton pairs by conventional quantum electrodynamics. $\ell = e$ or μ.

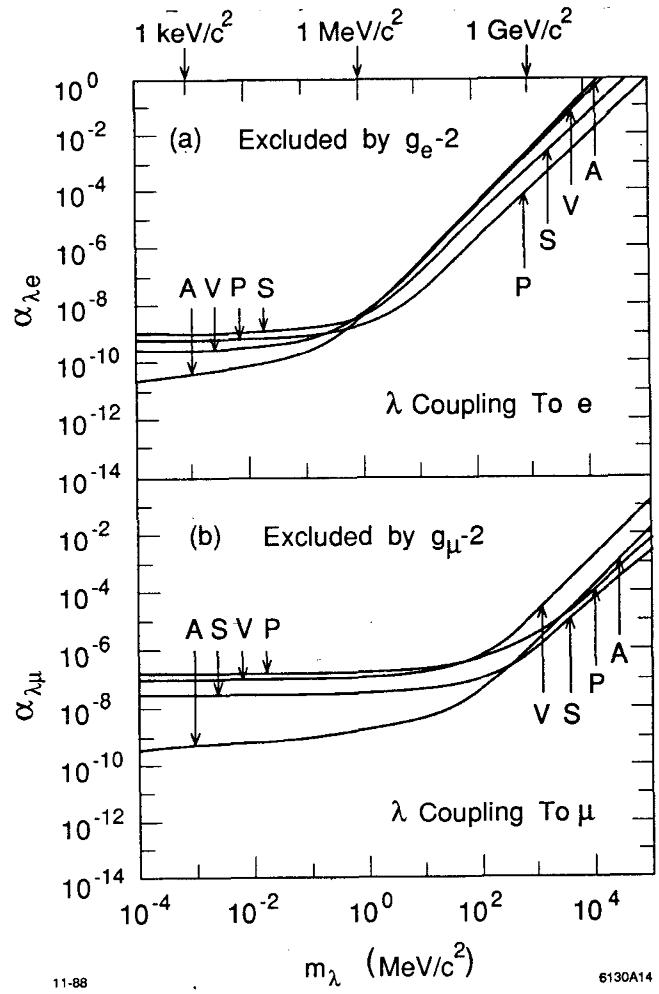

Fig. 6. Upper limits on $\alpha_{\lambda\ell}$ set by $g_\ell - 2$ measurements for (a) ℓ = electron and (b) ℓ = muon. A = axial vector, V = vector, P = pseudoscalar, S = scalar.

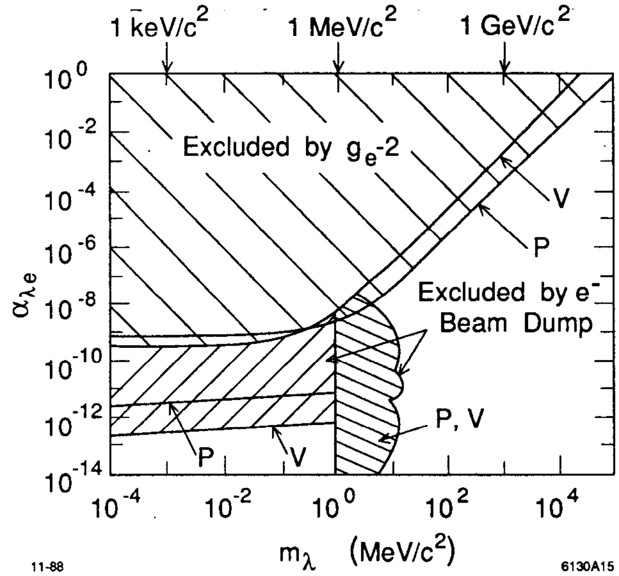

Fig. 7. Excluded regions of $\alpha_{\lambda e}$ versus m_λ from $g_e - 2$ and considerations of electron beam dump experiments. V = vector, P = pseudovector.

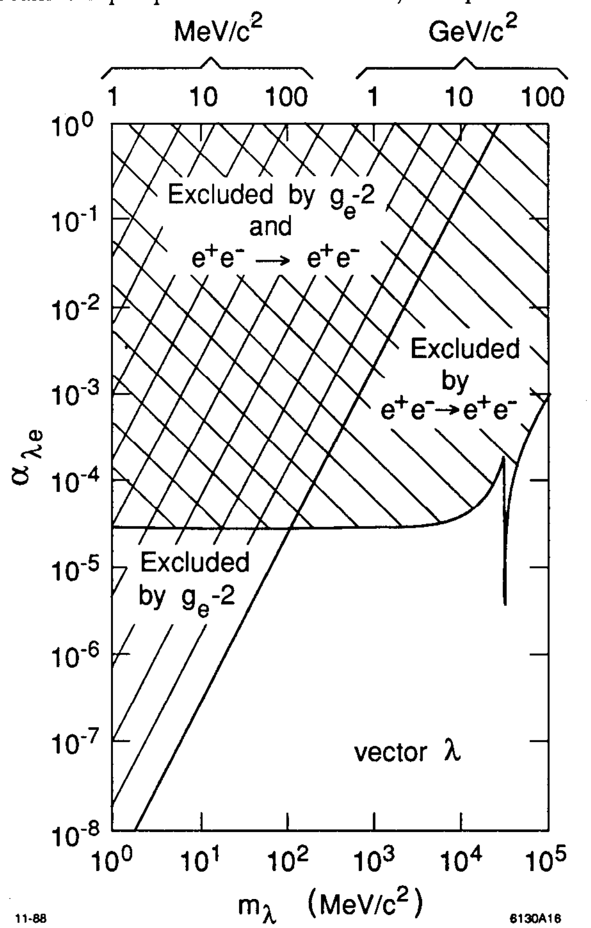

Fig. 8. Limits on $\alpha_{\lambda e}$ for a vector λ from $e^+e^- \to e^+e^-$ at 29 GeV and $g_e - 2$.

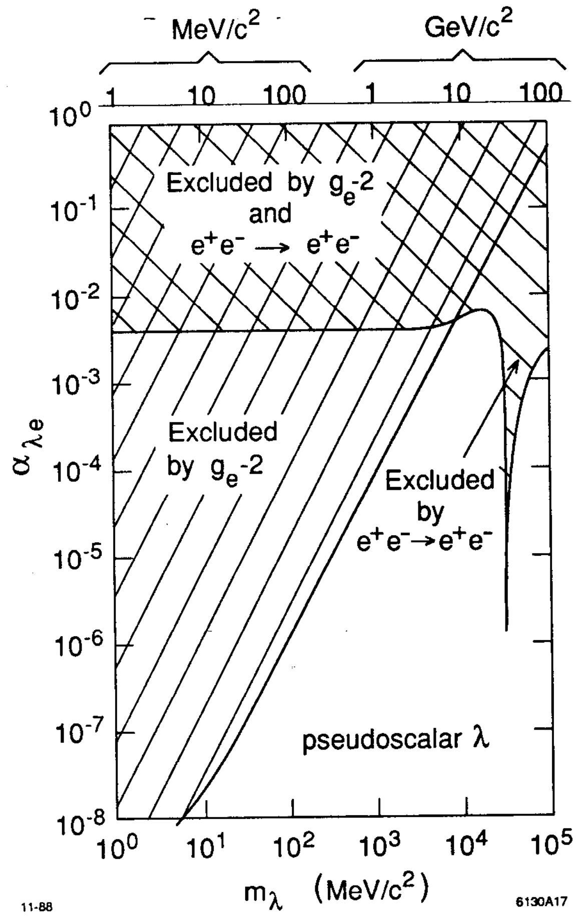

Fig. 9. Limits on $\alpha_{\lambda e}$ for a pseudoscalar λ from $e^+e^- \to e^+e^-$ at 29 GeV and $g_e - 2$.

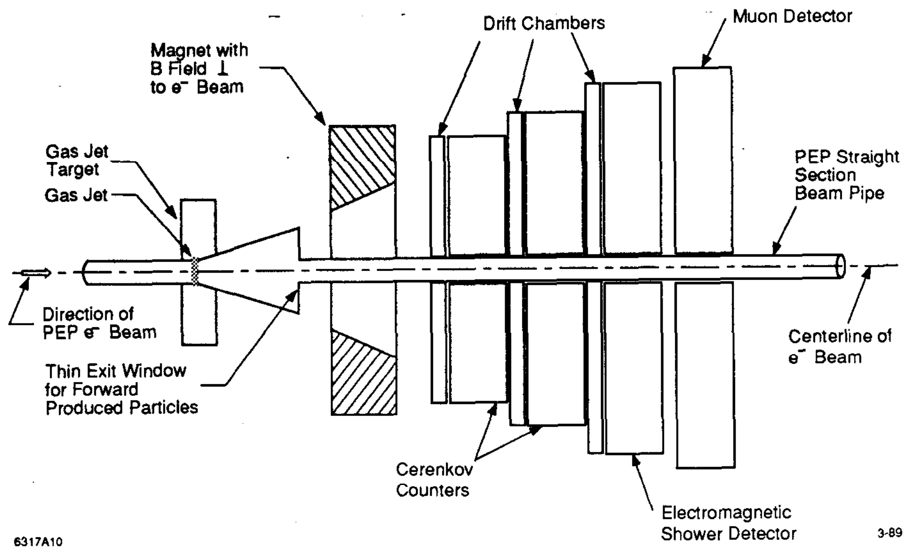

Fig. 10. Schematic vertical cross section of parts of PEGASYS to be used to study electroproduction of e^+e^- and $\mu^+\mu^-$ pairs. Not to scale. For clarity this schematic does not show the neutron and nuclear fragment detectors which surround the target at large and backward angles.

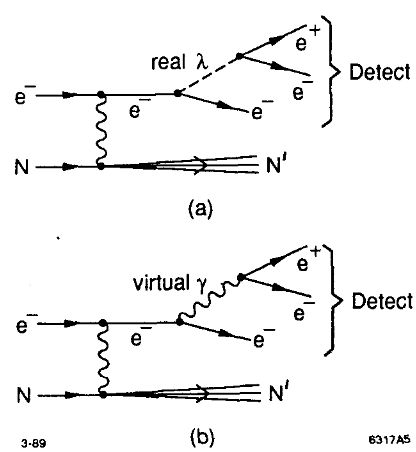

Fig. 11. Schematic of particle to be detected in the search for electroproduction of λ's with $\lambda \to e^+e^-$.