SLAC-PUB-1407

IS THE CROSS SECTION AT SPEAR TIME DEPENDENT?
(YET ANOTHER MODEL FOR e^+-e^- ANNIHILATION)

T. Goldman and Patrizio Vinciarelli
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

ADDENDUM

The authors would like to call attention to the following omissions in the preprint:

Page 2, line 13 should begin "build up.[23] As..."

Page 9 — The word "SPEAR" in line 5 should read "SPEAR[23]".

Footnote 5 should have the following sentence added:

"The first public suggestion of a "no-photon" mechanism that we know of was made by B. Richter at the Irvine Conference (December 1973, unpublished)."

Footnote 23 should be added:

23. Time (polarization)-dependent effects have been under active experimental consideration at SPEAR since December 1973; B. Richter and R. Schwitters, private communication.

The authors apologize for these omissions in the original manuscript.

SLAC-PUB-1407
(T/E)
April 1974

IS THE CROSS SECTION AT SPEAR TIME-DEPENDENT? (YET ANOTHER MODEL FOR e^+-e^- ANNIHILATION)*

T. Goldman† and Patrizio Vinciarelli ††
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

ABSTRACT

If e^+-$e^- \to \Phi \to$ hadrons, where Φ is a scalar, radiative beam polarization in storage rings will induce an apparent time-dependence of the cross section during an experimental run. This should provide a critical test for models which rely on such a scalar mechanism to enhance the cross section in the present energy range. A model of this kind is presented which identifies Φ with a composite Higg's field in gauge theories. We check for consistency with other processes and note that there may be an important relation to the shoulder in the di-muon mass distribution in $pp \to \mu^+\mu^- X$.

(Submitted for publication.)

---

* Work supported in part by the U. S. Atomic Energy Commission.

† National Research Council Post-doctoral Fellow.

†† Address after June 1: Theory Division, CERN.

Synchrotron radiation in an e^+e^- storage ring leads to transversely polarized beams where the electrons (positrons) are polarized antiparallel (parallel) to the guide magnetic field [1]. The magnitude of the polarization builds up toward a limiting value from the time of injection of the beams into the ring with a characteristic time constant dependent upon the energy and other machine parameters[2]. This effect may provide a useful constraint to model builders[3] as it has some interesting implications if the e^+e^- annihilation cross-section is not completely dominated by the one-photon mechanism as has conventionally been assumed[4]. In particular, the polarization dependence of other mechanisms will induce an apparent time dependence of the annihilation cross-section corresponding to the polarization build up. As an interesting example, we present here a particular "no-photon" model[5], which assumes that $\sigma_{e^+e^- \to}$ hadrons at the highest SPEAR energies is dominated by a heavy hadronic scalar (intermediate state) resonance which couples directly to neutral (scalar) leptonic currents. The origin of such a mechanism may find theoretical justification in a composite[6] Higg's scalar within the framework of gauge models of the strong and weak interactions[7,8].

It is simple enough to see how the difference in polarization dependence of the cross-section between one-photon and one-scalar intermediate states occurs. If an annihilating electron and positron both carry the same helicity and if there is no relative orbital angular momentum, then the total angular momentum state (J, J_z) is described by

$$|\tfrac{1}{2}, \tfrac{1}{2}\rangle_{e^-} |\tfrac{1}{2}, -\tfrac{1}{2}\rangle_{e^+} = \frac{1}{\sqrt{2}} |1, 0\rangle + \frac{1}{\sqrt{2}} |0, 0\rangle, \qquad (1)$$

where the z-axis is defined by the electron momentum vector at the annihilation point. From angular momentum conservation, the photon and scalar are seen to couple only to the first and second components, respectively, of the state in Eq. (1). Furthermore, the photon contribution vanishes for energies large compared to the electron mass as the photon decouples from the helicity non-conserving part of the current. We shall therefore refer to the total cross-section corresponding to the state of polarization described by Eq. (1) as $\frac{1}{2}\sigma_{\Phi}^{P}$. On the other hand, if the electron and positron have opposite helicity,

$$|\tfrac{1}{2},\tfrac{1}{2}>_{e^-}|\tfrac{1}{2},\tfrac{1}{2}>_{e^+} = |1,1>, \tag{2}$$

the scalar cannot contribute. We consequently denote the cross-section in this case as σ_{γ}^{P}. With unpolarized beams, these two cases occur with equal probability and the cross-section (σ_{TOT}^{U}) is given by:

$$\sigma_{TOT}^{U} = \tfrac{1}{2}\sigma_{\gamma}^{P} + \tfrac{1}{4}\sigma_{\Phi}^{P} . \tag{3}$$

With beams transversely polarized (direction of the guide magnetic field = x-axis), we have

$$\begin{aligned}|\tfrac{1}{2}, J_x=\tfrac{1}{2}>_{e^-}|\tfrac{1}{2}, J_x=-\tfrac{1}{2}>_{e^+} &= \frac{1}{\sqrt{2}}|1, J_x=0>+\frac{1}{\sqrt{2}}|0, J_x=0> \\ &= \frac{1}{2}|1, J_z=1>+\frac{1}{2}|1, J_z=-1>+\frac{1}{\sqrt{2}}|0, J_z=0>\end{aligned} \tag{4}$$

and

$$\sigma_{TOT}^{T} = \tfrac{1}{2}\sigma_{\gamma}^{P} + \tfrac{1}{2}\sigma_{\Phi}^{P} . \tag{5}$$

Combining Eqs. (3) and (5), we see that if P is the (common) polarization coefficient of the beams, then

$$\sigma_{TOT}(P) = \tfrac{1}{2}\,\sigma_\gamma^P + \tfrac{1}{4}\,(1 + |P|^2)\,\sigma_\Phi^P \ . \tag{6}$$

Thus, for a time dependent polarization as described in Ref. 2,

$$|P| = \frac{8\sqrt{3}}{15}\,(1 - e^{-\tau/\tau_o})(\tau_{dep}/(\tau_{pol} + \tau_{dep}))\ , \tag{7}$$

where τ = time from injection, τ_{pol} and τ_{dep} are machine-dependent time parameters and $\tau_o = (\frac{1}{\tau_{pol}} + \frac{1}{\tau_{dep}})^{-1}$, Eq. (6) predicts an apparently time-dependent cross-section that may change by up to a limiting factor of $[1+ \sim .85(\tau_{dep}/(\tau_{pol} + \tau_{dep}))^2]$ during an experimental run. We would like to stress that this effect is characteristic of a scalar contribution to the total annihilation cross-section and would provide a clear signal for the presence of such a contribution.

We shall now describe, at the phenomenological level, a model which adopts such a scalar mechanism to enhance the $e^+e^- \to$ hadrons cross-section in the present energy range. We shall show that the model yields non-trivial predictions for some processes other than e^+e^- annihilation, and that it easily survives all present experimental tests.

We postulate the existence of a hadronic scalar field Φ of mass m_Φ, with the quantum numbers of the vacuum[9] and which Yukawa-couples to leptons, l, and quarks, q, as described by the interaction Lagrangian density

$$L_I = h\bar{l}l\Phi + g\bar{q}q\Phi \ , \tag{8}$$

where $h \sim e^2$ and $g \sim 1$. The reader will recall that similar scalar fields are present in various gauge theory models of the weak and strong interactions.[7] These are the by now well known Higg's fields[10], which are conventionally introduced as elementary fields on the Lagrangian level. The effect of such fields other than the provision of the origin of symmetry breaking are usually minimized in those models by requiring that they be sufficiently massive. Our attitude is that they need not be so experimentally inaccessible and that they may indeed be responsible for the surprising results from SPEAR. We also feel that, purely within the context of gauge theories, there are notable advantages if such scalars are bound states[6]. Eq. (8) should therefore be regarded as describing an effective interaction accurate only in the neighborhood of the mass shells of the particles involved. Outside of this neighborhood, say for Φ significantly off-shell ($k^2 \neq m_\Phi^2$), h and g should be regarded as functions of k^2, $h(k^2)$ and $g(k^2)$.

A simple minded calculation[11] of the contribution of Φ to the unpolarized cross-section for e^+e^- annihilation into hadrons (see Figure) yields

$$\sigma_\Phi^U = \tfrac{1}{4}\,\sigma_\Phi^P = \frac{g^2(s)\,h^2(s)}{4\pi}\; s\,/\,((s-m_\Phi^2)^2 + m_\Phi^2\Gamma^2)) \quad , \tag{9}$$

where Γ is the width of Φ, and $g(k^2=s)$, $h(s)$ are presumably slowly varying functions for s in the neighborhood of m_Φ^2. Using Eq. (9) together with the usual one-photon (colored) quark-model contribution, it is easy to fit the preliminary SPEAR data[12] which are consistent with an approximately constant cross-section of ~23nb for 9 $GeV^2 \leq s \leq 25\ GeV^2$. However, given the magnitude of the reported error bars[12], and the number of parameters that are at our disposal in Eq. (9), as well as the quark-model parameter in the one-photon contribution, it is pointless to write down any particular fit at this time[13,14]. In any case, this is not our intent here as such a fit can be obtained from many different models[15] and our model is no more compelling than any other (except, perhaps, to gauge theorists already accustomed to the use of Higg's scalars). Rather, we want to point out that models of the kind presented here, although not inconsistent with the present data, are subject to critical polarization tests.

Of course, like any other, this model must meet the tests of many well-established experiments, and we discuss a few here briefly. Typically, when one fiddles with leptonic couplings one must maintain the good agreement of QED with such experiments as Bhabha scattering, $e^+e^- \to \mu^+\mu^-$, the value of (g-2) for the muon, and the Lamb shift in muonic atoms. The first two are clearly not affected, as the amplitudes calculated in QED in the one-photon Born approximation are of order e^2 and the analogous one-Φ contribution is of order $h^2 \sim e^4$. The one-virtual Φ vertex correction to the muon (g-2) is immediately seen to be of order $h^2 (m_\mu^2 / m_\Phi^2) \ln (m_\mu^2 / m_\Phi^2) \sim 10^{-4} e^4$, and higher order corrections are manifestly smaller. As present experiments are not yet sufficiently sensitive to severely test the order e^6 QED calculations (including estimates of hadronic corrections to the photon propagator), the effect of the Φ is obviously too small to be seen. The additional vertex correction contribution to the Lamb shift is negligible as it is of the same size. Besides this loop contribution, there is also a contribution from the effective potential due to a virtual Φ in the t-channel (replacing the photon). The ratio of this effect to that of the highest order Lamb shift calculation is

$\sim e^{-4} g(0)\, h(0)\ (m_\mu / m_\Phi)^2 \sim 10^{-4}/ e^2$ for muonic atoms even if we neglect the k^2-dependences of $g(k^2)$ and $h(k^2)$. Thus such an effect is also not experimentally detectable[16].

One of the main difficulties in the construction of sensible models is the need to reconcile the apparent lack of scaling[12] in the annihilation channel with the precocious character of scaling in the scattering channel[17], i.e., deep inelastic electroproduction as observed at SLAC. The contribution of Φ to the electroproduction structure functions $W_i(q^2, \nu)$ may be estimated by replacing photons by Φ's in a quark-model calculation : the ratio of the Φ-effect to the photon contribution is then of order $\alpha^{-2} h^2(q^2)\, g^2(q^2)\, (1+ m_\Phi^2/ |q^2|)^{-2}$. Thus, in the relatively low-q^2 region ($q^2 \sim 2-5$ GeV^2) the Φ contribution is suppressed by the propagator factor to the few per cent level. However, at the highest q^2 values at SLAC ($q^2 \sim 25$ GeV^2) this factor rises to $\sim \frac{1}{4}$ and one may need to invoke the extra suppression due to the q^2-dependence of the vertex functions $h(q^2)$ and $g(q^2)$, which reflect the composite nature of Φ. The need for the latter suppression mechanism may be even stronger to accomodate the μ-p scaling experiments at NAL.

There are many qualitative predictions implicit in the scalar Φ model. We have not sufficiently detailed the $\Phi \to$ multihadrons vertex to make specific statements about the hadronic final states. For instance, we cannot explain the large ratio ($\to 1$) of neutral to charged particles that has been observed at SPEAR, although the fact that Φ has opposite C-parity to the photon might be a clue. Nonetheless, one would naturally expect a typically hadronic fall-off in the transverse momentum distribution which is indeed observed[12]. Also, because Φ is a scalar and because it provides a growing contribution to the annihilation cross-section as $\sqrt{s}$ approaches the Φ-mass and as τ (time from beam injection) increases, the one-particle inclusive distribution as a function of θ (the angle between the detected particle and the beams) should behave like $1 + a(s,\tau)\cos^2\theta$ with $a(s,\tau)$ decreasing toward a small value ($<<1$) in that limit.

The Φ will be difficult to see in purely hadronic scattering experiments as we expect it to be very broad and to decay preferentially into multibody ($\sim 4-8$) final states not amenable to Dalitz plot analysis. Experiments where the effect of Φ might be visible include $e^-e^- \to e^-e^- + X$ (as at Doris) and $pp \to \mu + X$ (as at ISR or NAL). A more interesting and straightforward case is a double-arm experiment such as $pp \to \mu^+\mu^- + X$ as was carried out at Brookhaven[18,19]. Our mechanism

$$pp \to \Phi + X \quad \begin{array}{l} \\ \llcorner\!\!\to \mu^+\mu^- \end{array} \tag{10}$$

can easily account for the observed shoulder in the mass distribution of di-muon pairs [20,21] if $m_\Phi \simeq 4$ GeV, and $\Gamma \sim 1$ GeV. One may also turn the argument around and use it to predict that if the error bars on the SPEAR data can be reduced, <u>a peak in the annihilation cross-section at $s \simeq 16$ GeV^2 will be revealed</u>[22].

In conclusion, we have presented a model which appears to be consistent with present experiments. It leads us to a sharp relation between the unexpected results from CEA and SPEAR and the anomalous results in $pp \to \mu^+\mu^- + X$. We wish to reemphasize that models such as this which are sensitive to the naturally occurring polarization in colliding rings may be more easily and critically tested in such experiments than in any other way. Definite experimental results on the polarization dependence of the cross-section, now in progress at SPEAR, would therefore be of great help to model-builders.

We have enjoyed and benefited from conversations with J. D. Bjorken, S. Brodsky, Min-Shih Chen, S. Drell, E. Eichten, F. Gilman, Ling-Fong Li and B. Ward.

FOOTNOTES AND REFERENCES

1. V. N. Baier, Proc. of the International School of Physics, "Enrico Fermi", Physics with Intersecting Storage Rings (Academic Press, New York, 1971), p. 1; A. A. Sokolov, I. M. Ternov, Soviet Physics Doklady **8**, 1203 (1964).
2. R. F. Schwitters, "Spin Motion in e^+e^- Storage Rings", SLAC-PUB-1348 (I, A) November 1973.
3. Model builders could use some help as there is little to chose among a rapidly proliferating set of models; see Footnote 15 below for a partial list.
4. R. P. Feynman, Photon-Hadron Interactions (W. A. Benjamin, Massachusetts, 1972) pp 163-166.
5. Here we follow a classification scheme for e^+e^- models : "no-photon", "one-photon", "two-photon", ... , which was described to us by J. D. Bjorken, who has considered mechanisms in each category including scalars in the first. In the same category, J. D. Bjorken and I. Bigi have systematically analyzed the implications of a direct four-Fermi coupling of leptons to quarks.
6. T. Goldman and P. Vinciarelli, "Composite Higg's Fields and Finite Symmetry Breaking in Gauge Theories", SLAC-PUB-1357 (T), December 1973.
7. See for example S. Weinberg, Phys. Rev. Letters **31**, 494 (1973); H. Georgi and S. L. Glashow, Phys. Rev. Letters **32**, 438 (1974).
8. We thank I. Bars for pointing out the usefulness of a scalar similar to the one introduced here in resolving the $\pi - \eta$ degeneracy problem. See I. Bars and M. B. Halpern, "Pi-Eta Degeneracy Problem in Gauge Theories", Stanford University preprint ITP-456, Feb. 1974.
9. This may not be necessary, but it is conceptually the easiest case to analyze.
10. For references to the original literature see the review by E. S. Abers and B. W. Lee, Physics Reports **9C**, 1 (1974).

11. We adopt the usual parton model assumption that the quark-anti-quark rescattering into final states of ordinary hadrons does not significantly affect the form of the result.

12. We refer to the data as reported by B. Richter at the Irvine Conference (unpublished) and at the Chicago APS meeting (Feb. 4-7, 1974).

13. For example, if we assume $\Gamma/m_{\Phi} \sim \frac{1}{2}$, then m_{Φ} may lie anywhere in the range 4 to 10 GeV for reasonable values of g^2 (1 to 10). See below for a better estimate from $pp \rightarrow \mu^+\mu^- + X$.

14. Note that the contribution of Eq. (9) may be reasonably expected to die off faster than s^{-1} as $s \rightarrow \infty$ due to the assumed composite nature of Φ.

15. As these are to numerous to list completely, we can only note a few examples: H. R. Rubinstein, C. Ferro-Fontan, CERN preprint CERN-TH-1810; F. Renard, Montpellier preprint PM/73/10; J. C. Pati, A. Salam, Maryland preprint; G. B. West, Stanford preprint ITP-454; O. W. Greenberg, G. B. Yodh, Maryland preprint; H. Terazawa, Rockefeller preprint COO-2232B-38; J. Kogut, Cornell preprint CLNS-259; A. Sanda, NAL preprint NAL-PUB-74/16-THY; Minh Duong-van, SLAC preprint SLAC-PUB-1384 (T/E).

16. Although the QED calculation has been done to next higher order for ordinary atoms, the additional suppression of $(m_e/m_\mu)^2$ more than compensates.

17. M. Breidenbach et al., Phys. Rev. Letters 23, 935 (1969).

18. J. H. Christenson et al., Phys. Rev. D8, 2016 (1973).

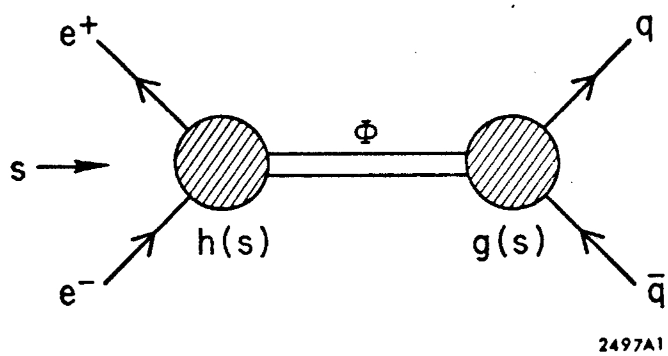
19. Note that this process, unlike $pp \rightarrow \gamma X \rightarrow \mu^+\mu^- X$, does not require a quark-anti-quark annihilation and so is not suppressed by the low probability of finding hard anti-quarks in the proton.

20. M. Einhorn and R. Savit have shown that this shoulder violates a quark model

upper bound on the di-muon mass distribution which follows from the Drell-Yan relation. We thank M. Einhorn for communicating this result to us prior to its appearance as a NAL preprint.

21. T. Goldman and P. Vinciarelli, to be published. The shoulder should also appear in muon-trident production and similar experiments: $\nu p \rightarrow \mu \Phi X \rightarrow \mu\mu\mu X$, $\mu p \rightarrow \mu \Phi X \rightarrow \mu\mu\mu X$, $ep \rightarrow e \Phi X \rightarrow e\mu\mu X$, etc. .

22. Note, however, that this relation, abstracted here from the scalar Φ model, can be expected to hold for any s-channel resonance model.



Contribution of Φ to the amplitude for $e^+e^- \rightarrow$ hadrons.