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THE TOTAL CROSS SECTION IN e^+e^- ANNIHILATION AND THE NEW PARTICLES*

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The total cross section[1] for the production of hadrons in electron-positron annihilation, $\sigma_{e^+e^- \to had}$, has some remarkable features. As shown in Fig. 1 $\sigma_{e^+e^- \to had}$ decreases by more than a factor of 10 as the total energy[2], E_{cm}, increases from 1 GeV to 7 GeV. Superimposed on this general trend are the very strong resonance peaks of the ρ^0, ω and φ vector mesons in the low energy region, and the very strong and very sharp ψ or J and ψ' peaks in the 3 to 4 GeV region (Table I). Finally in the 4 to 5 GeV region there are weaker but still distinct peaks. Perhaps the most remarkable feature is that we are able to explain almost all of these observations using only quantum electrodynamics, the quark model, and a little bit of faith. The purpose of this paper is to present this explanation and to point out what remains to be done.

We begin by ignoring the peaks in Fig. 1 and considering just the total cross section of the continuum, $\sigma_{e^+e^- \to had,\ cont}$. First let us see how far we can get using the Feynman diagram of Fig. 2a. In Fig. 2a the annihilation of the e^+ and e^- into a single virtual photon is easily calculated using quantum electrodynamics, but how are we to calculate the mysterious right hand vertex? For inspiration, as we often do in physics, we turn to a simpler problem -- the production of a $\mu^+\mu^-$ pair in e^+e^- annihilation. Using the Feynman diagram in Fig. 2b, we can easily calculate the total cross section for $\mu^+\mu^-$ production:

$$\sigma_{e^+e^- \to \mu^+\mu^-}(E_{cm}) = \frac{4\pi\alpha^2}{3E_{cm}^2} = \frac{86.8\ \text{nb}}{E_{cm}^2} \qquad (1)$$

Here α is the fine structure constant, the middle expression is in elementary particle units ($h = c = 1$), and in the rightmost expression E_{cm} is in GeV. The masses of the particles have been ignored.

The quark model postulates that the hadrons are composed of quarks, mesons consisting of a quark-antiquark pair, and baryons consisting of three quarks. Why not then decompose the mysterious vertex in Fig. 2a into a two step process as shown in Fig. 2c? First the virtual photon materializes into a quark-antiquark pair, $q\bar{q}$. Then the $q\bar{q}$ pairs annihilates into hadrons. If we assume, and it is here where a little faith is required, that:

a. the quarks are Dirac point particles with charge $\pm Qe$ (e being the electron charge),

b. the production of the $q\bar{q}$ pair is independent of their annihilation into hadrons;

then we can calculate the total cross section for this process. The $q\bar{q}$ pair production process is given by quantum electrodynamics; and since no free quarks have been found,[3] the probability of the $q\bar{q}$ pair annihilating into hadrons is 1. Indeed neglecting the quark mass we obtain a formula[4] analogous to Eq. 1

$$\sigma_{e^+e^- \to \text{had, cont}}(E_{cm}) = \frac{4\pi\alpha^2 Q^2}{3E_{cm}^2} \qquad (2)$$

Furthermore if there are N different kinds of quarks, each with charge $Q_n e$ and mass[5] m_n, there are n processes of the type in Fig. 2c. Then

$$\sigma_{e^+e^- \to \text{had, cont}}(E_{cm}) = \frac{4\pi\alpha^2 \sum_{n=1}^{N} Q_n^2}{3E_{cm}^2} \; ; \qquad (3a)$$

$$\text{for} \qquad E_{cm} \gg 2m_n, \; n=1,2 \ldots N \qquad (3b)$$

Here $\gg$ means at least 0.5 GeV or so greater.

This is such a simple and powerful idea that it has become conventional in e^+e^- annihilation physics to define

$$R(E_{cm}) = \frac{\sigma_{e^+e^- \to \text{had}}(E_{cm})}{\sigma_{e^+e^- \to \mu^+\mu^-}(E_{cm})} \qquad (4)$$

Then this theory predicts for the contimuum

$$R_{cont}(E_{cm}) = \sum_{n=1}^{N} Q_n^2 \quad ; \quad \text{all } m_n \ll E_{cm}/2 \tag{5}$$

Figure 3 shows the experimental values of R. Ignoring the resonances and peaks, we see that R varies between 1 and 6; therefore with the quark model we have already obtained the correct order of magnitude for $\sigma_{e^+e^- \to had}$!

Yet we can do even better. Before $\sigma_{e^+e^- \to had}$ was ever measured, the properties of the known hadrons required that a fractionally charged quark model contain the u,d,s quarks of Table II. And the spin-statistics properties of the baryons require that each of these quarks have an additional three-valued quantum number such as color associated with it. Using Table II and assuming the u,d,s quarks have masses of the order of 0.5 GeV/c^2 or less we calculate in the several GeV range

$$R_{u,d,s,cont} = 3\left[\left(\frac{2}{3}\right)^2 + \left(\frac{1}{3}\right)^2 + \left(\frac{1}{3}\right)^2\right] = 2 \tag{6}$$

As shown in Fig. 3 this fits the data in the $2 \lesssim E_{cm} \lesssim 3.5$ GeV range to within 20%. Quite an achievement for such a simple theory.

Now what about the jump in R which occurs around 4 GeV? To obtain such a jump using the quark model we must postulate that near 4 GeV we cross the threshold for the production of one or more additional $q\bar{q}$ pairs. The charm quark c, Table II, is an excellent candidate for such a threshold <u>if</u> we assign it a mass of about 2 GeV/c^2. First of all it provides for an increase in R of 4/3 since

$$R_{u,d,s,c,cont} = R_{u,d,s,cont} + 3\left(\frac{2}{3}\right)^2 = 3\frac{1}{3} \tag{7}$$

once E_{cm} is well above twice the mass of the charm quark, $2m_c$. I emphasize that the manner of the change in R from 2 to $3\frac{1}{3}$ as E_{cm} passes through the 4 GeV threshold region is not given by the simple theory of Fig. 2c. The R values in Eqs. 6 and 7 are asymptotic ones; and in the threshold energy region we expect an overshoot and perhaps even some wiggles in R.

The second reason for the introduction of a charm quark with mass about 2 GeV is that it simultaneously explains the existence of the ψ and ψ' peaks in the 3-4 GeV region. To understand this I interrupt the discussion of the continuum total cross section to discuss the total cross section for the resonances $\sigma_{e^+e^- \to \text{had,res}}$.

If a hadron has the quantum numbers of the photon: spin = 1, parity = -1, charge parity = -1, charge = 0, strangeness = 0 then the s-channel resonant process in Fig. 2d can occur. The ρ^o, ω and φ neutral vector mesons, Table I, have indeed these quantum numbers; and we see these resonant particles copiously produced in the low energy section of Fig. 1 Incidently for a resonant particle of mass m and spin J, a rough fit to $\sigma_{e^+e^- \to \text{had, res}}$ is provided by the relativistic Breit-Wigner formula:[6]

$$\sigma_{e^+e^- \to \text{had, res}}(E_{cm}) = \frac{\pi(2J+1)}{E_{cm}^2} \frac{4m^2\Gamma_{ee}\Gamma}{(E_{cm}^2 - m^2)^2 + m^2\Gamma^2} \qquad (8)$$

Here Γ_{ee} is the decay width of the resonance into an e^+e^- pair and Γ is the total decay width, Table I. The total hadronic cross section is obviously given by Eq. 8 combined with Eq. 3; explicitly

$$\sigma_{e^+e^- \to \text{had}} = \sigma_{e^+e^- \to \text{had,cont}} + \sigma_{e^+e^- \to \text{had,res}} \qquad (9)$$

Our next task is to connect these resonances with the quark model. This is easily done because in that model the ρ^o is a quantum mechanical mixture of bound states of $u\bar{u}$ and $d\bar{d}$ quark-antiquark pairs.[6] The ω and φ also contain $s\bar{s}$ pairs. The $\rho^{o\prime}$ with mass 1.6 GeV (which is not easily seen in Fig. 1) is an excited state of $u\bar{u}$ and $d\bar{d}$ pairs. Following this line of thought if there is a threshold for $c\bar{c}$ production (that is charm quark pair production) at 4 GeV; then somewhere below 4 GeV bound states of the $c\bar{c}$ pair should appear. And in fact they do appear since the simplest description of the ψ and ψ' is that they are bound states of $c\bar{c}$ pairs. That is, the ψ or J[4] and ψ'[4] are bound states of one charm quark and one charm antiquark. Hence the major peaks in $\sigma_{e^+e^- \to had}$ can be explained using the quark model and the Feynman diagram in Fig. 2d. (The relatively narrow widths of the ψ and ψ', Table I, can also be explained using the quark model and Zweig's rule[4], but we shall not take the space here to do so.)

Having explained the major peaks, we now turn to the minor peaks -- those in the 4 to 5 GeV region.[7] There is a clear peak at 4.41 GeV with width of 33 $\pm$ 10 MeV; and the structure in the 4.1 GeV region has one or more peaks. These are more complicated phenomena than the major peaks and they are only recently discovered.[7] At present we have only a partial understanding of the 4.1 GeV structure. It probably has some component produced by the changes in R as E_{cm} passes through the $2m_c$ threshold -- the overshoot or wiggle previously mentioned. It may contain one or more higher mass s-channel resonances which like the ψ and ψ' are $c\bar{c}$ bound states. And finally we know that the 4.1 structure is also related to the crossing of the threshold for the associated production of pairs of singly charmed mesons.[8] Singly charmed mesons consist of charm (c) quark and non-charm (u,d, or s) antiquarks or the charge conjugate pair. In particular in the 4.1 region we find the associated production of pairs such as $D^o\overline{D}^{o*}$.[8] The D^o has a mass of 1.865 GeV and a quark content $c\bar{u}$; the $\overline{D}^{o*}$ with a mass of slightly above 2.0 GeV is an excited state of the $\overline{D}^o$ and has quark content $\bar{c}u$. On the other hand the connection between singly charmed production and the 4.4 GeV peak is less well established -- we know nothing at present about the nature of the 4.4 GeV peak except that singly charmed mesons are also produced there.[8]

Having connected the peaks in $\sigma_{e^+e^- \to had}$ with the quark model, let us return to the continuum and Eq. 7. An R_{cont} value of $3\frac{1}{3}$ is predicted by Eq. 7;

but the experimental value of R_{cont} in the high E_{cm} region, above say 4.5 GeV, is 4.5 to 5.5. Are there more quarks with masses sufficiently low to contribute to $\sigma_{e^+e^- \to had,\ cont}$ in this region? We do not know. However there is a high probability that there is another source of hadrons in the high energy region -- a heavy lepton!

The production in e^+e^- annihilation of anomalous $e^{\pm}\mu^{\mp}$ pairs[9] and of anomalous single μ inclusive events[10] is most simply exaplain by the existence of a sequential heavy lepton[9], temporarily called the U particle[9], with a mass in the range $1.8 \lesssim m_U \lesssim 2.0$ GeV/c^2. The U would be produced through the reaction

$$e^+ + e^- \to U^+ + U^- \quad ; \tag{10}$$

the process being the same as that in Fig. 2b. Indeed once E_{cm} is somewhat larger than $2m_U$, the production cross section is

$$\sigma_{e^+e^- \to U^+U^-} = \frac{4\pi\alpha^2}{3E_{cm}^2} \tag{11}$$

the same as Eq. 1. This sequential heavy lepton would have a lifeline of 10^{-12} to 10^{-13} sec and the dominant decay modes would be

$$U^- \to \nu_U + e^- + \bar{\nu}_e$$
$$U^- \to \nu_U + \mu^- + \bar{\nu}_\mu$$
$$U^- \to \nu_U + \pi^-$$
$$U^- \to \nu_U + \rho^-$$
$$U^- \to \nu_U + \pi^+ + \pi^- + \pi^-$$

Here ν_U is a new neutrino carrying the unique lepton number of the U. If we accept the existence of this heavy lepton than <u>experimentally</u> all the decay modes of the U^+U pair produced in Eq. 10 are <u>counted</u> in $\sigma_{e^+e^- \to had}$. Even the purely leptonic decay modes are counted in at present. Then

$$\sigma_{e^+e^- \to had} = \sigma_{e^+e^- \to had,\ cont} + \sigma_{e^+e^- \to had,\ res} + \sigma_{e^+e^- \to U^+U^-} \tag{12}$$

When E_{cm} is somewhat larger than $2m_U$, $\sigma_{e^+e^- \to U^+U^-}$, Eq. 11, contributes one unit R. Hence we extend Eq. 7 and write

$$R_{u,d,s,c,cont} + R_{U^+U^-} = 4\frac{1}{3} \quad ; \quad \text{for } E_{cm} \gtrsim 4.5 \text{ GeV} \qquad (13)$$

This is as far as we can go at present towards our goal of explaining Figs. 1 and 3. We have yet to investigate the following fascinating questions:

a) Why does R = 4.5 to 5.5 rather than 4.3 for $E_{cm} > 4.5$ GeV?

b) How does R behave when $E_{cm} > 8$ GeV?

c) What is the precise nature and structure of $\sigma_{e^+e^- \to had}$ in the 4.1 GeV region?

d) What is the origin of the peak at 4.4 GeV?

e) Are there other minor peaks in $\sigma_{e^+e^- \to had}$ not yet found?

f) And finally there is an unanswered low energy question: What is R precisely in the $1 \lesssim E_{cm} \lesssim 2.5$ GeV region and does it agree with Eq. 6?

REFERENCES

1. Most of the data discussed in this paper was obtained by the SLAC-LBL Magnetic Detector Collaboration using the SPEAR e^+e^- colliding beams facility at the Stanford Linear Accelerator Center.
2. E_{cm}, the total energy in the $e^+ - e^-$ interaction, is equal to twice the energy in either the e^+ or e^- beam.
3. The alternative theory which holds that free quarks can exist leads to the same result. These quarks would have short lifetimes, decaying primarily into hadrons before they can be detected.
4. For a general reference see G.J. Feldman and M.L. Perl, Physics Reports 19c, 234(1975). References to the discovery of the ψ or J particle and the ψ' particle are given here.
5. In ascribing masses to the quarks we are also engaging in an act of faith since free quarks have never been detected and there are strong forces between quarks.
6. M.L. Perl High Energy Hadron Physics (Wiley, New York, 1974).
7. J. Siegrist *et al.*, Phys. Rev. Letters 36, 700(1976).
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9. M.L. Perl *et al.*, Phys. Letters 63B, 466(1976) and references contained therein.
10. G.J. Feldman *et al.*, to be published.
11. R.F. Schwitters and K. Strauch, Ann. Rev. Nucl. Sci. 26, 89(1976).

TABLE I

Properties of some vector mesons with quantum numbers of photon. Γ is the total width which appears in Eq. 8

Name	Mass (MeV)	Γ(MeV)
ρ^{0}	773	152.
ω	783	10.0
φ	1020	4.1
ρ'	1600	200. - 800.
ψ	3098	0.067
ψ'	3684	0.228

TABLE II

Properties of the previously accepted u,d,s quarks and the recently accepted c quark. I, I_z, Q, B, S and C are the isotopic spin, z component of the isotopic spin, charge, baryon number, strangeness and charm.

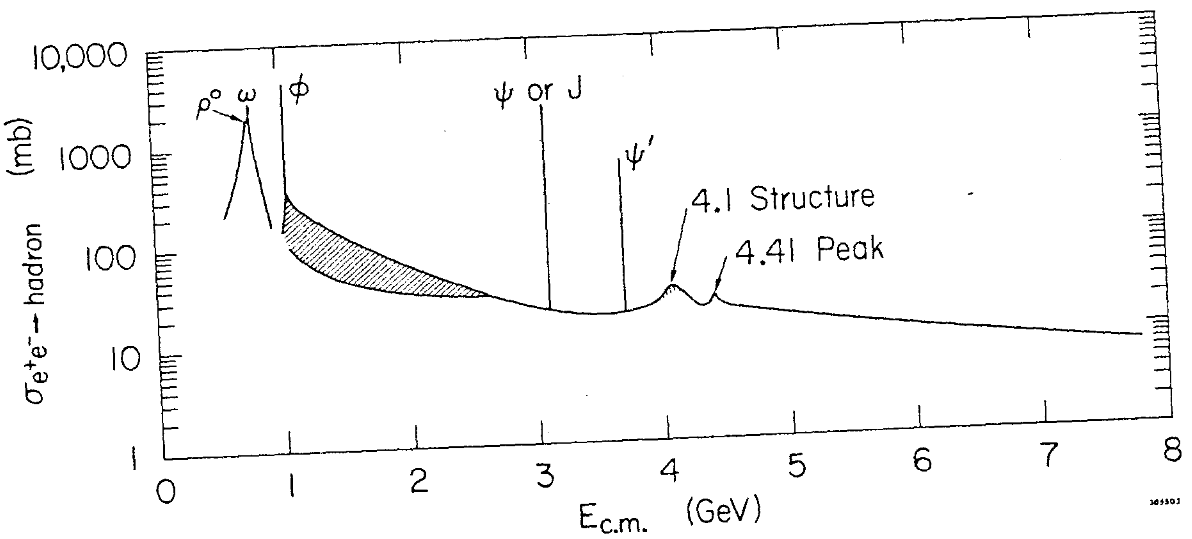
Name	u	d	s	c
Other Name	p	n	λ	p'
I	1/2	1/2	0	0
I_z	+1/2	-1/2	0	0
Q	+2/3	-1/3	-1/3	+2/3
B	1/3	1/3	1/3	1/3
S	0	0	-1	0
C	0	0	0	1

FIGURE CAPTIONS

FIG. 1 Simplified presentation of $\sigma_{e^+e^- \to had}$ versus E_{cm}. The shaded areas indicate large uncertainties in the value of $\sigma_{e^+e^- \to had}$. See Fig. 3 for a detailed presentation of the experimental errors and uncertanties.

FIG. 2 Feynman diagrams for: (a) the general production of hadrons in e^+e^- annihilation, (b) the reaction $e^+ + e^- \to \mu^+ + \mu^-$, (c) the production of hadrons thru quark-antiquark pair production, and (d) the production of hadrons thru an s-channel resonance.

FIG. 3 $R = \sigma_{e^+e^- \to had}/\sigma_{e^+e^- \to \mu^+\mu^-}$ versus E_{cm}. Taken from Ref. 11.



10,000
1000
100
10
1
$\sigma_{e^+e^- \to \text{hadron}}$ (mb)
ρ^0
ω
ϕ
ψ or J
ψ'
4.1 Structure
4.41 Peak
0
1
2
3
4
5
6
7
8
$E_{c.m.}$ (GeV)

Fig. 1

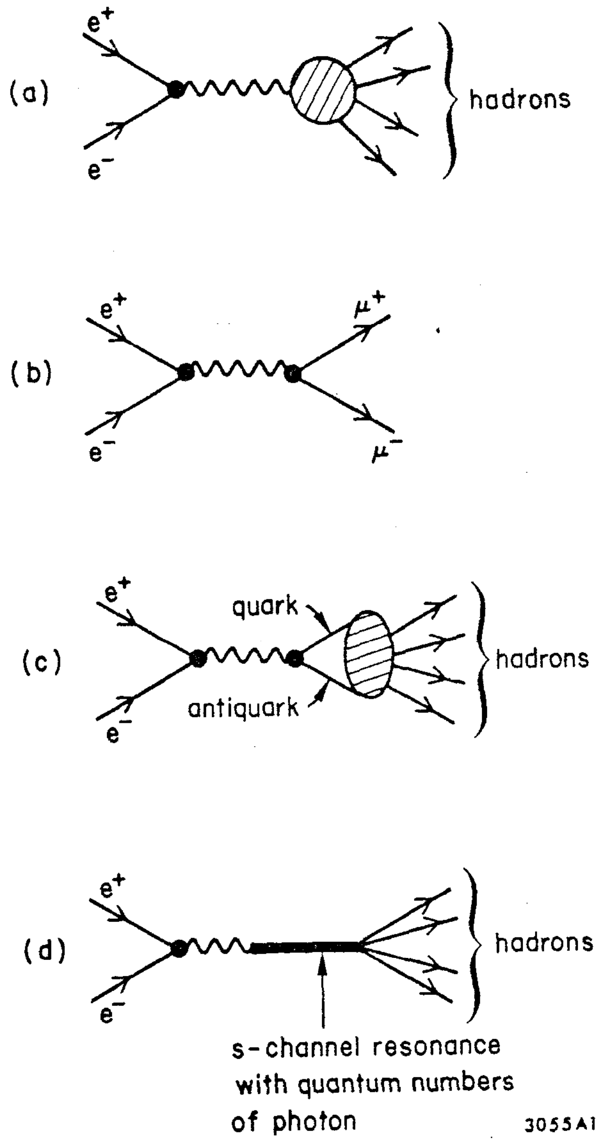

(a)
e+
e−
hadrons
(b)
e+
e−
μ+
μ−
(c)
e+
e−
quark
antiquark
hadrons
(d)
e+
e−
hadrons
s-channel resonance
with quantum numbers
of photon
3055A1

Fig. 2

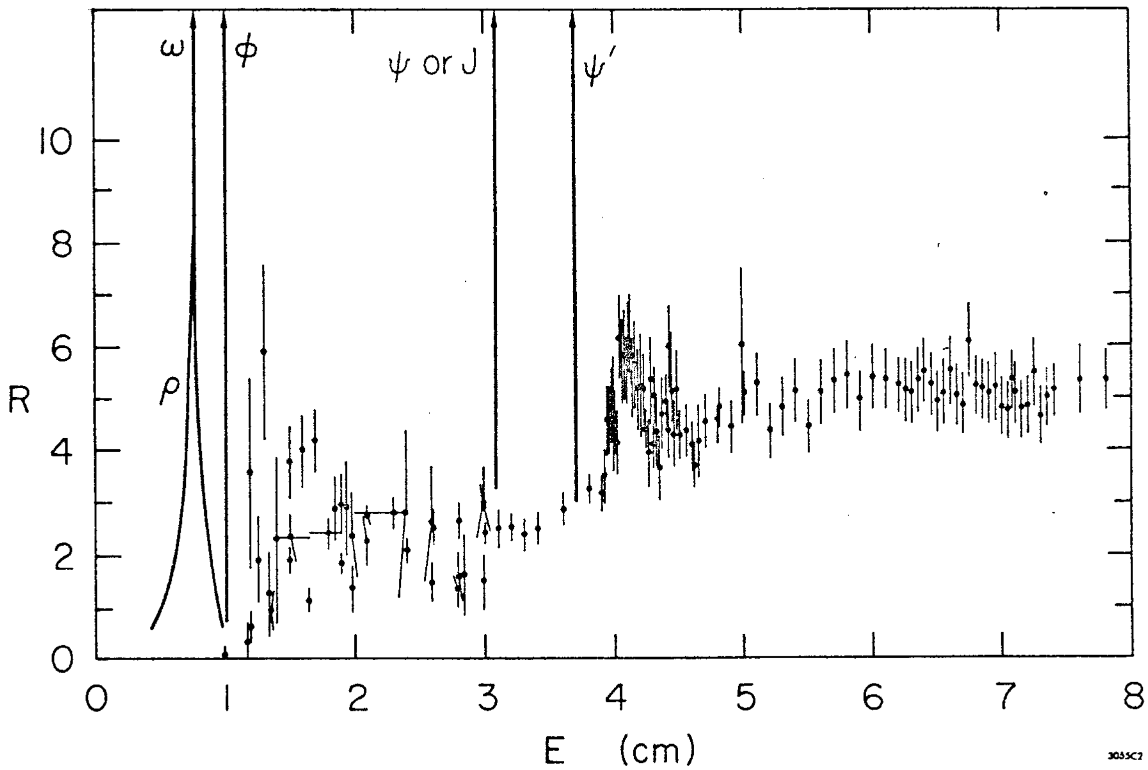


Fig. 3