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PRODUCTION OF NEW PARTICLES IN ELECTRON-POSITRON ANNIHILATION*

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I. INTRODUCTION

At last year's conference in this series, I recall speaking[1] in a session on "Psychotherapy and Neuroses". But at that time, with charmed particles still to be directly observed and with a number of important puzzles to be solved, in many ways I felt like someone presenting problems rather than cures. With the experimental progress in the year since then, the present discussion should be much more reassuring.

In fact, most of the major components of the "new physics" in electron-positron annihilation appear to have fallen into place. In particular, we have a whole spectroscopy of "bound charm" states followed at higher energies by the production of pairs of particles manifesting "naked charm". So far there is no indication that the properties of the new, weakly decaying mesons deviate from those expected for charmed mesons, properties which were deduced, or deducible, from the classic Glashow, Iliopoulos, and Maiani paper[2] of 1970.[3]

So, with no great discovery in electron-positron annihilation for six months, I will review a number of areas where there is important progress, but of a more detailed quantitative nature. In doing so, I will touch on the charmonium states, on charmed mesons, and on the evidence for a charged heavy lepton. A number of topics discussed at some length in my talk[4] at the Brookhaven APS Meeting will not be covered here.

Therefore, this talk may be viewed in some regards as trying to tie up some of the loose ends that were left over from a year ago. As such, it is also symptomatic of an era I think has already begun of filling in details within the broad outline of the physics of electron-positron annihilation which is now established.

II. CHARMONIUM

The available experimental evidence points strongly to the new narrow states below ~ 3.7 GeV being the ground state plus orbital and radial excitations of a fermion-antifermion system. The general situation with respect to this "charmonium" system has been recently reviewed elsewhere[4] and we concentrate here on more specialized subjects where there have been very recent developments.

There is increasing evidence that these states are singlets not only with respect to SU(2), i.e., have zero isospin, but also with respect to SU(3). For some time we have known[5] that only upper limits were set for ψ decay into $K_S K_L$, $K^*\bar{K}^*$, $K^{**}\bar{K}^{**}$, and $K\bar{K}^{**}$, but that decays into KK^* and K^*K^{**} are clearly seen.[6] Such a pattern of unseen and observed decay modes corresponds exactly to that of the forbidden and allowed decays of an SU(3) singlet with odd charge conjugation.[7]

The recent paper of Vannucci et al.[8] on mesonic decays of the ψ contains branching ratios (or upper limits) for these and many other modes. This permits further tests of the SU(3) singlet assignment of the ψ such as the relative branching fractions into $\pi\rho$, $K\bar{K}^*$, and $\eta\phi$, or into ρA_2, $K^*\bar{K}^{**}$, ωf, and $\phi f'$.

Tests for the SU(3) singlet character of each of the three states between ψ and ψ' identified with the ^3P charmonium levels comes from their relative decays[9] to $\rho^o\pi^+\pi^-$ vs $K^{*o}K^-\pi^+$. For $\chi(3414)$ there is also the ratio of the $\pi^+\pi^-$ to K^+K^- branching ratios.[9]

All these measurements are consistent with SU(3) singlet assignments for the corresponding states. In particular, the results reported by Vannucci et al.[8] and corresponding measurements at DESY[10] are consistent, and point toward such an assignment for the $\psi(3095)$. There seems to be some symmetry breaking present in the decay mechanism for $\psi \rightarrow$ pseudoscalar meson plus vector meson where Vannucci et al. report relative branching ratios for $\pi^+\rho^-$: $K^+\bar{K}^{*-}$: $\eta\phi = 2.1 \pm 0.5 : 0.8 \pm 0.15 : 0.5 \pm 0.3$, whereas theory (for an SU(3) singlet ψ with p-wave phase space) would give $1 : 0.85 : 0.5$. However, if expressed in terms of octet and singlet amplitudes for the final state, this corresponds to a 10 to 20% ratio of octet to singlet amplitude. Such a level of symmetry breaking is roughly the same as found in some "ordinary" hadron decays,[11] and should therefore cause no alarm as to the basic conclusion that the ψ and other charmonium states are consistent with being SU(3) singlets.

The small widths of <u>all</u> the charmonium states below ~ 3.7 GeV are conventionally explained by the Okubo-Zweig-Iizuka rule,[12] for the charmed quark and antiquark composing the charmonium do not appear in the hadrons making up the decay products and the corresponding quark diagram is disconnected. A striking result taken from the list of branching ratios[8] for ψ decays is that

$$\Gamma(\psi \rightarrow \omega f)/\Gamma(\psi \rightarrow \omega f') \gtrsim 10$$

(only an upper limit exists[8] for $\psi \rightarrow \omega f'$). Note that in terms of quark diagrams $\psi \rightarrow \omega f'$ (with ω-ϕ and f-f' ideally mixed) corresponds to a doubly disconnected one. Thus we see a substantial extra suppression in rate in the case of a decay corresponding to a doubly rather than singly disconnected quark diagram. In the same vein, $\psi \rightarrow \phi f'$ is seen, but $\psi \rightarrow \phi f$ is not. An extra disconnection gives extra suppression!

This statement may not appear to jibe with the milder suppression (of $\sim 1/5$) of $\phi\pi^+\pi^-$ (which corresponds to a doubly disconnected quark diagram) compared to $\omega\pi^+\pi^-$ (which can correspond to a singly disconnected one) reported earlier.[5] However, I would argue this ratio of overall rates gives a misleading impression of what is happening. A look (Fig. 1) at the $\pi^+\pi^-$ mass spectrum produced in association with an ω or ϕ shows them to be entirely different. There are almost no $\pi^+\pi^-$ events above 1 GeV produced along with a ϕ, whereas a majority of dipions associated with an ω lie there. Just below 1 GeV, where the $\pi^+\pi^-$ mass distribution associated with a ϕ is concentrated, that associated with an ω has a valley.

A possible mechanism to understand this, which is consistent with the experimental observations, is as follows: The final state ϕ is made together with a resonance containing a strange quark-strange antiquark ($s\bar{s}$) pair. Such a process corresponds to a singly disconnected diagram, since the ϕ is almost entirely $s\bar{s}$. If the mass of the $s\bar{s}$ system is less than about 1 GeV (e.g., for the ϵ or S*) it decays into $\pi\pi$, since $K\bar{K}$ is kinematically forbidden. On the other hand, if the mass is greater than 1 GeV, and particularly if the state is dominantly composed of $s\bar{s}$ (e.g., the f'), it decays to $K\bar{K}$. In other words, the second disconnection associated with the $\phi\pi\pi$ final state takes place at low mass, "inside" a resonance, and is at least partly due to phase space inhibiting the $K\bar{K}$ mode. At high mass, the ratio of $\phi\pi\pi$ to $\omega\pi\pi$ events and the absence of $\psi \rightarrow \omega f'$ and $\psi \rightarrow \phi f$ indicates a considerably larger suppression of decays corresponding to doubly disconnected diagrams.

The list of observed mesonic decays of the ψ now available, plus the constraints of zero isospin and isospin conservation in the decay process, permit putting bounds on the branching ratio for decays into final channels with the same particle types and multiplicity, but different charge combinations. Thus, the observations of ψ decay modes with particular charge assignments in the 3π, 5π, 7π, 9π, $K\bar{K}\pi$, $K\bar{K}2\pi$, $K\bar{K}3\pi$, $K\bar{K}4\pi$, and $2K2\bar{K}$ channels allow establishment of a lower bound[8] of $21.6 \pm 2.4\%$ for the ψ branching fraction into all charge assignments for these channels. A model in which all isospin states are populated statistically gives 30.2 ± 3.3% for the sum of these channels on the basis of the same observations[8] of modes with particular charge assignments.

These newer, more detailed, numbers for individual modes, and the corresponding bounds or estimates for the sum of both observed and unobserved decays, agree quite well with the overall picture of ψ decays discussed previously.[1] When added to the known branching ratios for e^+e^-, $\mu^+\mu^-$, decay into hadrons through a virtual photon, and estimates of modes involving higher K and π multiplicity or baryons, a large majority of all ψ decays are accounted for.

An important change in accounting for the ψ' decays has occurred, however. The present status[13] of this is as follows:

TABLE I

ψ' Branching Ratios

Mode	Branching Ratio (%)
$\psi' \to e^+e^-, \mu^+\mu^-$	2
$\to \gamma_V \to$ hadrons	3
$\to$ hadrons (direct decays)	~ 10
$\to \pi\pi\psi$	~ 50
$\to \eta\psi$	4
$\to \gamma + {}^3P_J$ (J = 0, 1, 2)	18-28
$\to \gamma + \chi(3455)$	$\gtrsim 1$
Total	88-98

The estimated width for ψ' direct decays to hadrons is simply scaled[1] from the corresponding width for the ψ by the ratio of $\Gamma(\psi' \to e^+e^-)$ to $\Gamma(\psi \to e^+e^-)$. What is mostly new here are the gamma decay rates into the ${}^3P_J$ states between the ψ and ψ' taken from the results of the MP^2S^3D collaboration[14] at SPEAR as well as the SLAC-LBL magnetic detector collaboration.[15] The individual branching ratios for these decays have probable values of 7 to 8%, and are at or even above the previous upper limits.[16] As a result the "missing" decays of the ψ' may now be in place. There is no longer any need to find other major ψ' modes, although presently undetectable ones at the 10% level cannot be ruled out.

With the new knowledge of, for example, BR ($\psi' \to \gamma\chi(3414)$), together with older measurements of $\psi' \to \gamma\chi \to \gamma$ + hadrons we can extract branching ratios for various χ decays. Using isospin invariance we then may convert branching ratios for particular modes into lower bounds on general modes of the same multiplicity or, using a statistical model, into estimates of the rate for the general mode. For the $\chi(3414)$ this exercise yields the following:[17]

TABLE II

$\chi(3414)$ Branching Ratios

Mode	Branching Ratio (%) Lower Bound	Branching Ratio (%) Statistical Model
$\pi\pi$	1.4 ± 0.5	1.4 ± 0.5
4π	8.0 ± 1.5	10.7 ± 2.0
6π	4.1 ± 1.5	9.8 ± 3.7
$K\bar{K}$	1.9 ± 0.6	1.9 ± 0.6
$K\bar{K}\pi\pi$	10.8 ± 2.7	14.4 ± 3.6
Total	26.2 ± 3.5	38.2 ± 5.6

Thus at least ~ 25% of all $\chi(3414)$ decays are accounted for, and probably almost 40%. We have come a long way since the first information on the hadronic decays of the ψ!

III. CHARMED MESONS

The neutral charmed meson D^0 with mass ~ 1865 MeV is observed[18] to decay into $K^-\pi^+$, $K_S^0\pi^+\pi^-$, and $K^-\pi^+\pi^-\pi^+$ from e^+e^- annihilation experiments,[18,19] and possibly $K_S^0\pi^+\pi^-\pi^+\pi^-$ in photoproduction.[20] Its charged partner D^+ has been observed[21] in the nonleptonic mode $K^-\pi^+\pi^+$. Work on establishing cross section times branching ratio values for these and other modes, or providing upper-bounds, is in progress.

It is of considerable interest to know the actual branching ratio of the D^0 into, say, $K^-\pi^+$. Since all that is measured at the moment is the product of production cross section and branching ratio at some particular e^+e^- center-of-mass energy, this now requires a guesstimate of the total production cross section for the D^0. Taking charm production at $\sqrt{Q^2} = 4.028$ GeV as being 10 to 15 nb, between 0.5 and 1.0 D^0 per event containing charm (there is also D^+ production in these events), and a cross section times branching ratio[22] for $e^+e^- \rightarrow (D^0 \rightarrow K^-\pi^+) + \ldots$ of ~ 0.25 nb, one finds that BR $(D^0 \rightarrow K^-\pi^+)$ lies between approximately 1.5 and 5%. The branching ratios for other nonleptonic modes may all be estimated by comparison to $K^-\pi^+$.

An estimate of the semileptonic decay rates of charmed particles from e^+e^- annihilation data also can be obtained in much the same way as for the $K^-\pi^+$ nonleptonic decay of the D^0. Both the DASP[23] and PLUTO[24] groups working at DESY give peak cross sections[25,26] for inclusive anomalous $e^\pm$ production of ~ 3 nb near 4.03 GeV e^+e^- center-of-mass energy. If, again, the inclusive charm production is 10 to 15 nb at this energy, then one deduces a branching ratio for semielectronic decay of some weighted average of the D^0 and D^+ of 10 to 15%.

An analogous estimate can be made from the recent data[27] obtained using the muon tower and magnetic detector at SPEAR on anomalous muon production. For momenta above 910 MeV and an average e^+e^- center-of-mass energy of 6.9 GeV, it is found that $\sim 2.2\%$ of charged tracks are muons in events with ≥ 3 observed charged prongs. Taking a charged multiplicity of 5, assuming that the ratio of 2.2% for anomalous muons to charged tracks is true for momenta below

910 MeV also, and the guesstimate that 1/3 of the events with four or more charged particles at such center-of-mass energies contain charmed particles, one deduces[28] a semimuonic branching ratio of $\sim 17\%$. Note that at these energies one is likely producing a mix of not only D^0 and D^+, but also the F^+ and charmed baryons, all of which may have different branching ratios.

From these estimates, as well as the rate for dilepton production in neutrino-induced events,[29] it now seems very likely that the semielectronic and semimuonic branching ratios for some charmed particles are each in the 10 to 20% range, for a total semileptonic branching ratio of 20 to 40%. This implies that there is little or no enhancement of the rate for nonleptonic as compared to semileptonic decays above the naive level obtained by assuming the charmed quark decays as if it were free into $s + e^+\nu$, $s + \mu^+\nu$, $s + u\bar{d}$ in the ratios 1:1:3.

From study of D production near 4 GeV we know that it occurs principally via two-body or quasi-two-body modes, e.g., $e^+e^- \to D^0\bar{D}^{*0}$. If one then observes the decay of $D^0 \to K^-\pi^+$, the angular distribution of the K (or π) relative to the beam and D line-of-flight directions may be studied. Calling ψ the angle between the D line of flight and the incident e^+ beam direction, and θ, ϕ the polar and azimuthal angles of the K relative to the $e^+e^- \to D\bar{D}^*$ production plane with z axis along the D line of flight, one can show that the angular distribution of the K has the form[30,31]

$$W(\psi,\theta,\phi) \propto \frac{1+\cos^2\psi}{2} W_T(\theta) + \frac{1-\cos^2\psi}{2}\cos 2\phi\, W_P(\theta) + \frac{1-\cos^2\psi}{2} W_L(\theta) + \frac{\cos\psi\sin\psi}{\sqrt{2}}\cos\phi\, W_I(\theta) \; . \tag{1}$$

The structure functions $W_T(\theta)$, $W_P(\theta)$, $W_L(\theta)$, and $W_I(\theta)$ have forms which are characteristic of the D and D* spins and are generally interdependent in a nontrivial way for any particular set of spin assignments. This should make it possible, at least for low values of the spins of D and D*,[30,31] to use the data to rule out all but a single assignment for the D and D*.

There appears to be substantial D production in e^+e^- annihilation in the 4 GeV region, and in particular at the bumps in the cross section at 4.028, ~4.11, and 4.414 GeV. Also, from SPEAR data there has been no evidence of $e^+e^- \rightarrow \psi + \ldots$, with upper bounds on the cross section for this process previously reported[32] as being in the range of 1% of $\sigma(e^+e^- \rightarrow \text{hadrons})$. Note that, from our experience with $\psi' \rightarrow \pi\pi\psi$, if the vector resonances in the 4 GeV region are higher mass relatives of the ψ and ψ', then we might well expect widths for these states to decay to $\pi\pi\psi$, $4\pi\psi$, $\eta\psi$, etc., to be tens to hundreds of keV. Since the total width of these vector states lies in the tens of MeV range, branching ratios into $\psi + \ldots$ might be expected to be 10^{-3} to 10^{-2}. Anything much larger might well be an indication that some of these states are not simply further radial excitations of the $c\bar{c}$ system, decaying primarily in a Zweig rule allowed manner into pairs of charmed mesons, but possibly $c\bar{q}\bar{c}q$ states, e.g., "molecular charmonium". Such an assignment of some of the states in the 4 GeV region has been considered by a number of authors,[33,34,35] including the possible decay chain $c\bar{q}\bar{c}q \rightarrow c\bar{c} + q\bar{q}$. The smallness of any signal[32] for inclusive ψ production in the 4 GeV region would seem to be evidence against such an assignment of states, together with a decay chain leading to charmonium levels among the final particles.

A good deal of the information we presently have on D masses and D spectroscopy comes from a careful study of the recoil mass spectra recoiling against a detected D. Equivalently, at a fixed e^+e^- center-of-mass energy, one studies the D momentum or kinetic energy spectrum.

The recoil mass spectrum against a detected D^0 for all data from 3.9 to 4.6 GeV is shown in Fig. 2. The peaks near 1.87 GeV and 2.01 GeV are indicative of $D^0\bar{D}^0$ and $D^0\bar{D}^{*0}$ production (as well as kinematic reflections from $D^*\bar{D}$ with D^* decay into a detected D with emission of a pion or photon). The peak near 2.15 GeV is likely due to $D^*\bar{D}^*$ production with detection of a D^0 from D^* decay.[36] The collection of events above ~2.4 GeV indicates yet other D^0 production mechanisms, possibly including higher D resonances in this mass region.

The D^0 momentum or kinetic energy spectrum at $\sqrt{Q^2} = 4.028$ GeV has been particularly useful in extracting properties of the D^0 and D^{*0} from the peaks due to the channels $D\bar{D}$, $D\bar{D}^* + \bar{D}D^*$, and $\bar{D}^*D^*$. Preliminary results from this effort are as follows:[22]

$$M_{D^{*0}} = 2005.5 \pm 1.5 \text{ MeV}, \tag{2}$$

which is measured relative to $E_{beam} = 2014$ MeV. The Q-value for $D^{*0} \rightarrow \pi^0 D^0$ is 3 ± 2 MeV, which gives

$$M_{D^0} = 1867 \pm 3 \text{ MeV}. \tag{3}$$

Furthermore, with such a small Q-value, $D^{*0} \rightarrow \gamma D^0$ is expected to be competitive with $D^{*0} \rightarrow \pi^0 D^0$; and it is:[22]

$$\frac{BR(D^{*0} \rightarrow \gamma D^0)}{BR(D^{*0} \rightarrow \pi^0 D^0)} = 1.0 \pm 0.3 . \tag{4}$$

The D^+ spectrum has more background and it is harder to get unique fits. However, the peak from $D^+\bar{D}^{*-}$ is rather clear, and it gives[22]

$$M_{D^+} + M_{D^{*+}} = 3880 \pm 5 \text{ MeV}. \tag{5}$$

Subtracting the previously listed D^0 and D^{*0} masses, one finds

$$(M_{D^+} - M_{D^0}) + (M_{D^{*+}} - M_{D^{*0}}) = 7 \pm 6 \text{ MeV} . \qquad (6)$$

Since both mass differences are expected to be positive and of the same order, each is probably 2 to 8 MeV.[4] Such values are at the lower end of the range of theoretically predicted ones.

IV. HEAVY LEPTONS

We start the discussion of heavy leptons in antihistorical order with the work on anomalous muon production in e^+e^- annihilation using the muon tower and magnetic detector at SPEAR.[27] In particular we focus on events with only two charged particles detected, with a cut on the angle between the planes containing the charged tracks and the beam to be greater than 20° and with a cut on the missing mass squared (against the two charged prongs) to be greater than 1.5 GeV^2. Both cuts serve to limit QED backgrounds. Again, the momentum of the potential muon must be greater than 910 MeV, to distinguish it (statistically) from hadrons on the basis of its penetration of the matter in the muon tower.

After subtraction of remaining QED background, muons from pion and kaon decay, and hadron "punch through" the muon tower, a significant anomalous muon signal remains. In particular, for e^+e^- center-of-mass energies of 5.8 to 7.8 GeV (average 6.9 GeV), the cross section for anomalous muon production in two prong events with the above cuts[27] is (Fig. 3):

$$\sigma(e^+e^- \to \mu^\pm + \text{one charged track} + \ldots) = 212 \pm 49 \text{ pb} .$$

Although a cross section of a few hundred picobarns sounds negligibly small, in fact it is big on the scale of electron-positron interactions at these energies. To see this we do the following rough calculation. First we make a correction for the cuts, particularly those for the muon momentum and the coplanarity angle. A rough correction for both of these multiplies the cross section by about a factor of three to obtain an estimated cross section without cuts for $\mu^{\pm}$ + one charged track + ... of ~ 640 pb.

Now, such anomalous muons must arise from either production of a new hadron, carrying a quantum number conserved in strong and electromagnetic interactions so that it decays semileptonically, or the production of a heavy lepton. In either case we have pair production of these new particles along with their antiparticle. In the case of a new hadron it is likely that additional hadrons are produced:

$$e^+e^- \rightarrow U + \bar{U} + \ldots ,$$

whereas a heavy lepton would be pair produced with no other particles. We take the production cross section for this process to be that for muon pairs, i.e., the point fermion cross section, which is ~ 1.6 nb at these energies. Recall that the inclusive production of hadrons containing a new charge 2/3 (-1/3) quark is expected to be $\frac{4}{3}\sigma_{\text{point}}$ ($\frac{1}{3}\sigma_{\text{point}}$), while pair production of charged heavy leptons (well above threshold) is given by σ_{point}.

Putting the factors together, we have[37]

$$2 \times \sigma(e^+e^- \rightarrow U+\bar{U}+\ldots) \times BR(U \rightarrow \mu+\ldots) \times BR(\bar{U}+\ldots \rightarrow \text{one charged prong} + \ldots) \simeq 640 \text{ nb.}$$

With $\sigma(e^+e^- \rightarrow U+\bar{U}+\ldots) = 1.6$ nb, we deduce that

$$BR(U \rightarrow \mu + \ldots) \gtrsim 0.2$$

by using $BR(\bar{U}+\ldots \rightarrow \text{one charged prong} + \ldots) \leq 1$. By μ-e universality we then must have a new particle[38] with a branching ratio into an electron or muon plus neutrals of $\sim 40\%$!

Furthermore, the momentum spectrum of the detected muons is hard (Fig. 4), and different from the (soft) spectrum seen in events with $\gtrsim 3$ charged particles detected. This, together with the estimated branching ratio given above, makes it very difficult to associate the U with a hadron, and in particular with charmed particles. For our experience with the D's teaches us that their momentum spectrum in e^+e^- annihilation is not hard and that the momentum spectrum of the leptons in their semileptonic decay is quite soft. Folding together these two spectra then gives an inclusive anomalous lepton spectrum in e^+e^- annihilation from D production which is soft.[39] We expect this to be true generally for leptons originating from decays of new hadrons. Furthermore, all known D decays involve K mesons, as expected theoretically. These, together with the pions expected to be produced in association with <u>any hadron</u> well above threshold, would typically yield several additional charged prongs in each event containing new hadrons, thus throwing it out of the μ + one charged particle topology. Finally, for the case of charmed particles we already have accounted for a 20 to 40% semileptonic branching ratio from ≥ 3 prong events. We would have difficulty accommodating another $\sim 40\%$ from 2 prong events!

Thus, of the explanations offered, the least strained and outlandish is that we have the production of a charged heavy lepton plus antilepton. This single explanation is consistent with the anomalous muon production data[40] and all other data up to this time. These include:

1. Anomalous $e\mu$ Events. Historically events of the form $e^+e^- \rightarrow e^{\pm}\mu^{\mp}$ + undetected neutrals were the first indication[41] of anomalous events which might indicate the existence of a charged heavy lepton. The energy dependence of the observed cross section is consistent with that expected for pair production of a point fermion-antifermion. Analysis[42] of the distribution of the angle between the electron and muon and its energy dependence gives evidence for the source of the events being production of a pair of fixed mass particles, with the Lorentz transformation from the

heavy lepton rest frame to the lab resulting in the e and μ being thrown increasingly back-to-back at higher e^+e^- energies. Further, the momentum spectrum of the leptons indicates[42] a three body rather than two body decay of the U. From these distributions one also deduces the mass to lie between 1.6 and 2.0 GeV, with values in the upper half of this range more likely.[43] Assuming that the decays involving a muon or electron are $\nu\mu\bar{\nu}_\mu$ and $\nu e\bar{\nu}_e$, respectively, and that these occur with equal branching ratio, then the observed cross sections give[42]

$$\mathrm{BR}(\mathrm{U} \rightarrow \mu\bar{\nu}\nu) = \mathrm{BR}(\mathrm{U} \rightarrow e\bar{\nu}\nu) = 17^{+6}_{-3}\% .$$

2. Anomalous ee and $\mu\mu$ Events. Although the QED backgrounds are much higher, there is evidence[44] for the analogs of the $e\mu$ events, but where the leptons are e^+e^- or $\mu^+\mu^-$. They occur at a rate consistent with the branching ratio given above for $\mathrm{U} \rightarrow \nu e\bar{\nu}_e$ or $\mathrm{U} \rightarrow \nu\mu\bar{\nu}_\mu$.

3. $\mu^\mp$ hadron$^\pm$ + neutrals Events. A subset of the $\mu^\pm$ + one charged prong +... events discussed at the outset of this section contains sufficient identification of the other charged particle to indicate that it is not an electron or muon.[43,27] Such events should occur when one heavy lepton decays to $\nu\mu\bar{\nu}_\mu$ and the other, for example, to $\nu\pi$ or $\nu\rho$. The rate for these latter two decays relative to the $\nu\mu\bar{\nu}_\mu$ decay is calculable from otherwise known parameters and the observed $\mu^\mp$ hadron$^\pm$ + neutrals events occur at a rate consistent with this.[43]

4. Two-Prong Topological Cross Section. Because the great majority of decays of a ~ 2 GeV heavy lepton involve a single charged prong ($\nu\mu\bar{\nu}_\mu$, $\nu e^-\bar{\nu}_e$, $\nu\pi^-$, $\nu\rho^-$, $\nu\pi^-\pi^0\pi^0$, ...), pair production of heavy leptons with a mass of ~ 2 GeV probably involves two charged particles $\sim 80\%$ of the time.

Crossing the threshold for heavy lepton production should then result in a jump in the two prong topological cross section. As the e^+e^- center-of-mass energy increases, the average multiplicity in hadronic events rises and hadron production feeds the two prong topology less and less; but the heavy lepton decays are fixed in character and so its contribution will increasingly dominate the two prongs, which in turn will increasingly stick out in the distribution of the cross section into topologies. This provides an amusing analog to the situation in high energy hadron collisions where diffraction dissociation feeds (relatively fixed) low multiplicities while the multiperipheral mechanism results in increasing average multiplicity as the energy rises.

Assuming the existence of a heavy lepton, not only are the exact values of the parameters associated with it of great interest, but it may be used to gain information on other physical parameters or particle properties. For example, assuming the heavy lepton has its own neutrino, ν_U, so that its decay involving a muon is $U^- \to \mu^- \bar{\nu}_\mu \nu_U$, the muon momentum spectrum already restricts[42] the mass of ν_U to be less than 700 MeV. Limits (or observation!) on modes like $U \to e\gamma$ or $\mu\gamma$, and more precise branching ratios for observed modes will provide important restrictions on the existence and properties of the spectroscopy and couplings of leptons.

In several ways the existence of a charged heavy lepton is the most exciting of all the spectacular discoveries made in electron-positron annihilation during the past few years. Unlike the charmed quark and its associated hadronic spectroscopy, nobody had a good reason for proposing such a particle beforehand. And particularly with the discovery of charm, neatly closing the books at four quarks and four leptons, there seemed every reason not to want such a particle.

Now, more than ever, the pattern of quark and lepton masses is a mystery, and there is a high likelihood that still more fundamental fermions remain to be found.

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28. Similar estimates based on the muon tower data were first made by G. J. Feldman, whom I thank for discussions. We take only the data with ≥ 3 charged prongs observed to make this estimate of semimuonic charm decays, since the corresponding two prong events likely arise dominantly from the decay of a charged heavy lepton. See Section IV of this talk.

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31. Some of the special low spin cases have also been considered by J. D. Jackson (unpublished).

32. G. J. Feldman, invited talk at the Irvine Conference, December 1975 (unpublished). H. Meyer (Ref. 26) reports an inclusive ψ production cross section in the 4 GeV region which is a few tenths of a percent of the total cross section.

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37. We assume that the muon and the other charged prong don't both come from the U (or $\bar{U}$).

38. If there are several new hadrons, then we are computing an average (weighted by relative production cross section) branching ratio, assuming the sum of their inclusive production cross sections is σ_{point}.

39. See, for example, A. Ali and T. C. Yang, DESY preprint DESY 76/39 (1976), unpublished; V. Barger, T. Gottshalk, and R.J.N. Phillips, University of Wisconsin preprint COO-881-569 (1976), unpublished; M. Gronau et al., DESY preprint DESY 76/62 (1976), unpublished.

40. Note that the previous rough calculation of BR ($U \to \mu + \ldots$) is in fact an estimate of BR ($U^- \to \nu\mu^-\bar{\nu}_\mu$) in the case that U is a charged heavy lepton and it decays dominantly into one charged prong plus neutrals. The shape and magnitude of the inclusive muon spectrum of Ref. 27 agree with the

heavy lepton hypothesis.

41. M. L. Perl et al., Phys. Rev. Lett. 35, 1489 (1975).

42. M. L. Perl, G. J. Feldman et al., Phys. Lett. 63B, 466 (1976).

43. See G. J. Feldman, lecture at the SLAC Summer Institute on Particle Physics, Stanford University, 2-13 Aug 1976, and SLAC-PUB-1852 (1976), unpublished.

44. See also H. Meyer, Ref. 26, for evidence from the PLUTO detector at DESY for μ + one charged prong and $\mu^{\mp}e^{\pm}$ events in the 4 GeV region at rates consistent with the cross sections measured at SPEAR (Refs. 41, 42, and 27).

45. M. L. Perl, invited talk at the International Neutrino Conference 1976, Aachen, Germany, 8-12 June 1976, and SLAC-PUB-1764 (1976), unpublished.

46. G. Goldhaber, talk at the Topical Conference of the SLAC Summer Institute on Particle Physics, Stanford University, 2-13 Aug 1976, and LBL preprint LBL-5534 (1976), unpublished.

FIGURE CAPTIONS

1. Invariant mass of the $\pi^+\pi^-$ system in the decays (a) $\psi \to \phi\pi^+\pi^-$, (b) $\psi \to \omega\pi^+\pi^-$. Invariant mass of the K^+K^- system in the decays (c) $\psi \to \phi K^+K^-$, (d) $\psi \to \omega K^+K^-$. The dashed lines indicate the shape predicted by phase space corrected for detection biases (from Ref. 8).

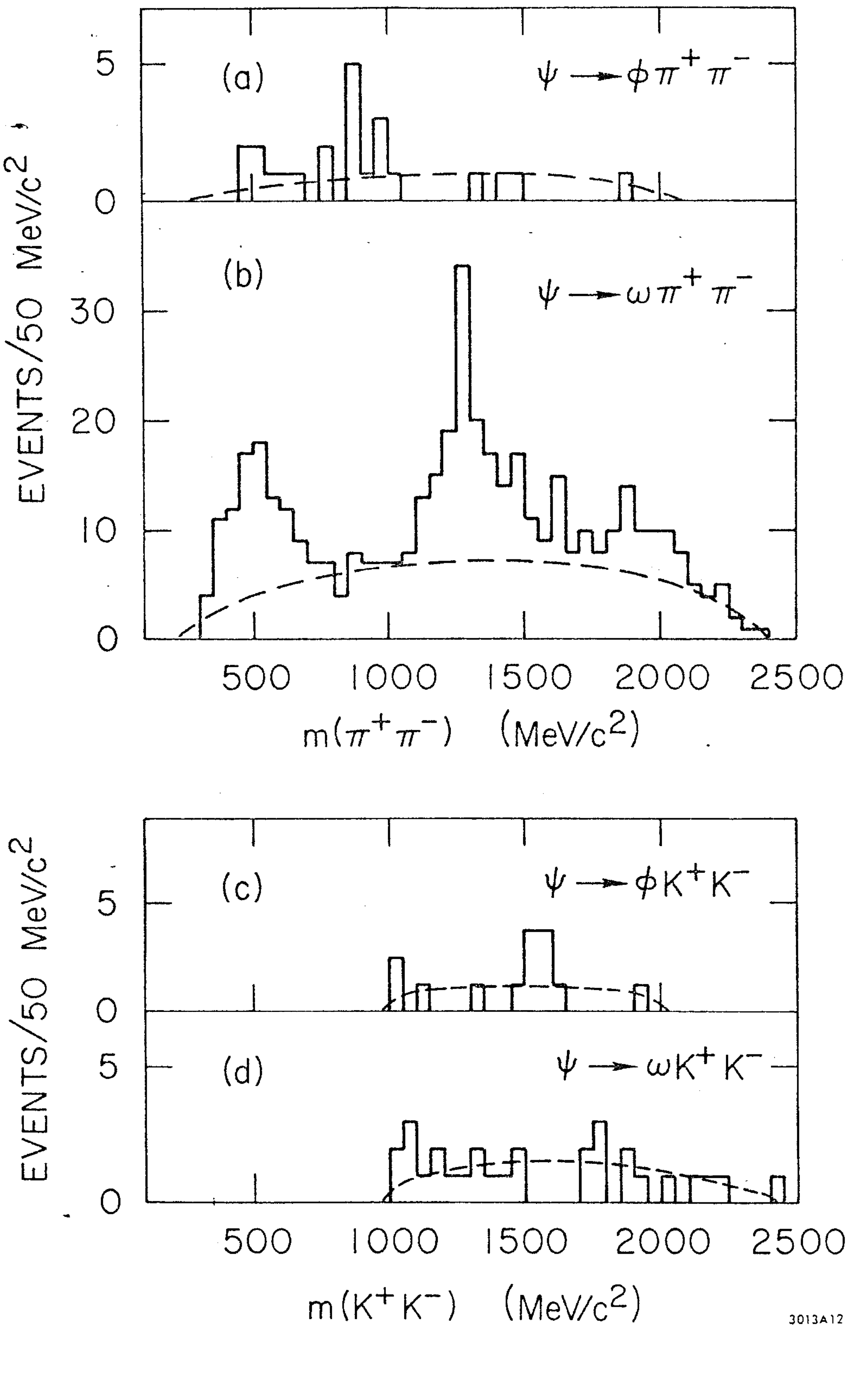
2. (a) M_{recoil} distribution for the $K^{\pm}\pi^{\mp}$ signal as measured.

   (b) M_{recoil} distribution for the $K^{\pm}\pi^{\mp}$ signal for fixed $M_{K\pi}$ = 1865 MeV. Each distribution is background subtracted. Data are from e^+e^- annihilation from 3.9 to 4.6 GeV (from Ref. 46).

3. (a) Anomalous muon production cross section vs the number of charged prongs observed.

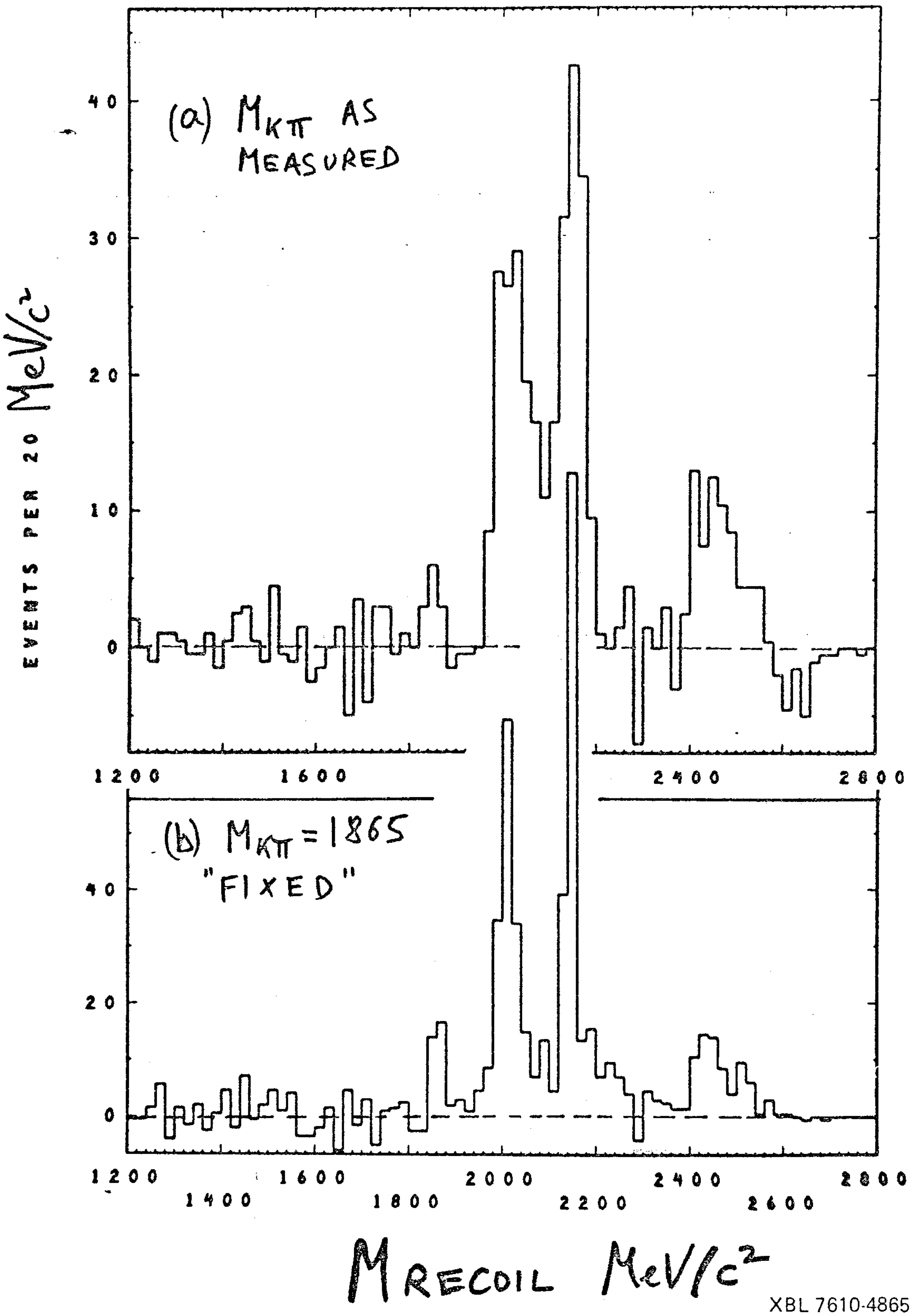
   (b) Ratio of anomalous muons to candidates vs the number of charged prongs observed in the $E_{c.m.}$ range 5.8 to 7.8 GeV (from Ref. 27).

4. Differential cross section for anomalous muon production versus momentum for (a) two prong events and (b) multiprong events in the $E_{c.m.}$ range 5.8 to 7.8 GeV (from Ref. 27).



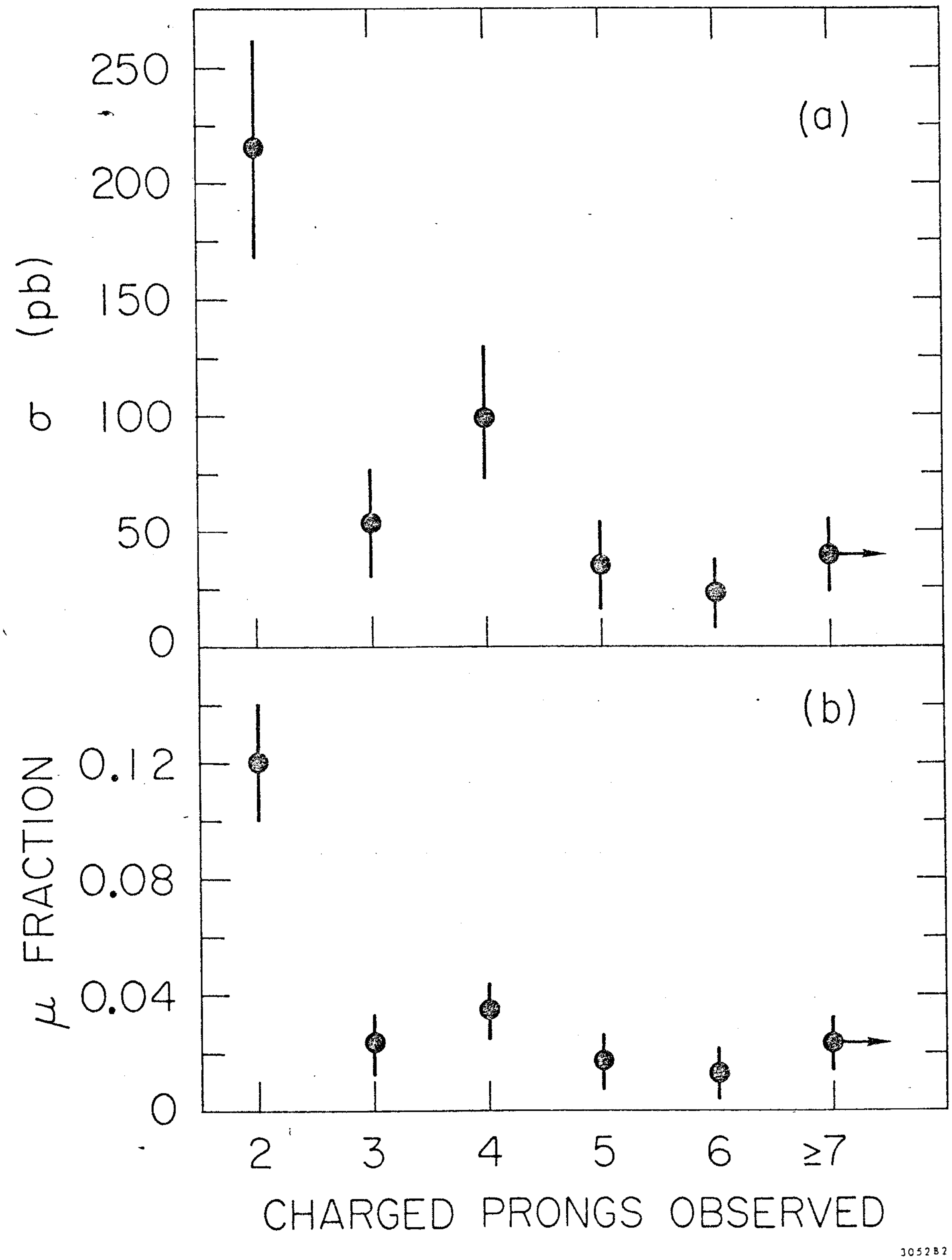
EVENTS/50 MeV/c2
5
0
(a)
ψ → φπ+π−
(b)
ψ → ωπ+π−
30
20
10
0
500
1000
1500
2000
2500
m(π+π−) (MeV/c2)
EVENTS/50 MeV/c2
5
0
(c)
ψ → φK+K−
5
0
(d)
ψ → ωK+K−
500
1000
1500
2000
2500
m(K+K−) (MeV/c2)
3013A12

Fig. 1



(a) $M_{K\pi}$ AS MEASURED
(b) $M_{K\pi}$ = 1865 "FIXED"
EVENTS PER 20 MeV/c²
M RECOIL MeV/c²
XBL 7610-4865

Fig. 2



250
200
150
100
50
0
σ (pb)
(a)
(b)
0.12
0.08
0.04
0
μ FRACTION
2
3
4
5
6
≥7
CHARGED PRONGS OBSERVED
3052B2

Fig. 3

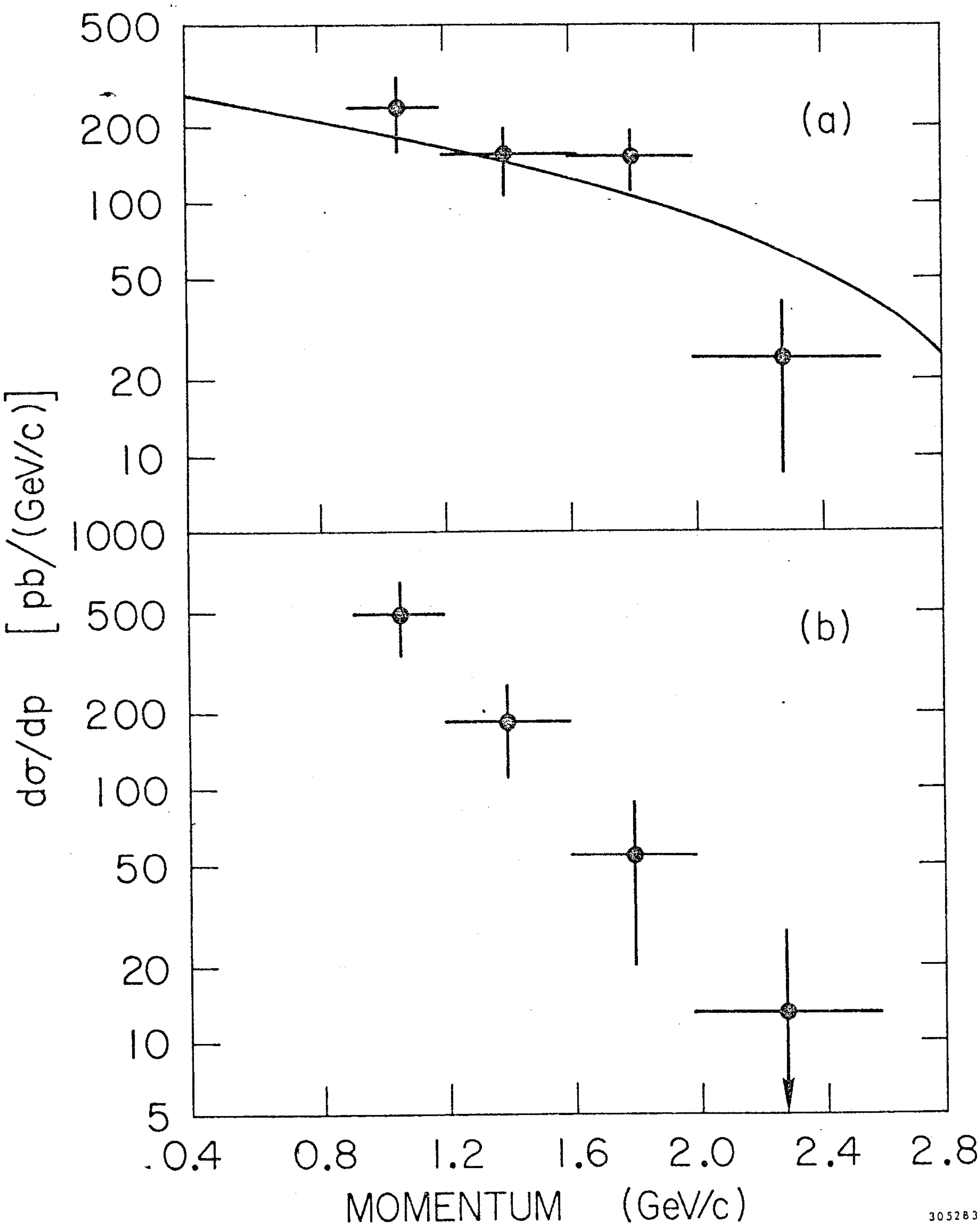

500
200
100
50
20
10
(a)
1000
500
200
100
50
20
10
5
(b)
dσ/dp [pb/(GeV/c)]
.0.4
0.8
1.2
1.6
2.0
2.4
2.8
MOMENTUM (GeV/c)
305283

Fig. 4