Submitted to Comments on Nuclear and
Particle Physics

LBL-6101
Preprint C.

THE CASE FOR CHARMED MESONS

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March 1977

Prepared for the U. S. Energy Research and
Development Administration under Contract W-7405-ENG-48

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LBL-6101
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THE CASE FOR CHARMED MESONS*

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*Work supported by the U.S. Energy Research and Development Administration.

In May-June 1976 we have observed a narrow state[1,2] at SPEAR with the SLAC-LBL detector, at a mass $M \approx 1865$ MeV/c^2, decaying into $K^{\mp}\pi^{\pm}$, $K^{\mp}\pi^{\pm}\pi^{+}\pi^{-}$ and the exotic $K^{\mp}\pi^{\pm}\pi^{\pm}$.

A first reaction might be: very interesting -- so the physics community has yet another K^*!

What leads us to the belief that we have something new and very different here?

A. The Circumstantial Evidence

As discussed in Perl's article[3] the energy region in which we made our observation, $\sqrt{s} = 3.9 - 4.6$ GeV, has a very special location. At 3.1 and 3.7 GeV we have the very narrow states ψ/J and ψ' respectively.[4] Just beyond the ψ' the ratio $R = \sigma_{hadron}/\sigma_{\mu\mu}$ undergoes a rather abrupt increase from ~ 2.5 to ~ 5. Beyond 3.9 GeV R has further structure, a very broad peak at ~ 4.1 GeV with possible substructure and a peak with $\Gamma = 30$ MeV at ~ 4.4 GeV.

Thus we see all the earmarks of narrow "bound" states* below 3.7 GeV, the ψ/J and ψ' with the quantum numbers of the photon. Furthermore, additional "bound" states with quantum numbers different from those of the photon, three to four** X states,[5] reached by radiative decay from the ψ' and a possible state[6] X(2800) reached by radiative decay of the ψ. Those are followed at higher $\sqrt{s}$ values (above 3.8 GeV) by broad peaks, presumably no longer "bound" states.

The current interpretation is that these narrow particles are isosinglet states of a new quark-antiquark pair $Q\bar{Q}$ and that their decay is inhibited by the Okubo-Zweig-Iizuka (OZI) rule where the final states do not contain the

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*Here the term "bound" state is used to indicate that the decays are inhibited by a factor of ~ 1000 over the normal strong interaction rates.

**X(3415), X(3500) $\equiv P_c$, X(3550) and possibly X(3450).

new quarks. This is similar to the case of the φ made up of $s\bar{s}$ whose decay to ρπ is inhibited by the OZI rule as well.

The inhibition due to the OZI rule no longer applies as soon as the threshold energy is reached where the production of a pair of new mesons M and $\bar{M}$, each of which contain this new quark type Q and $\bar{Q}$ respectively, together with an old type quark ($\bar{q}_i$ and q_i respectively) becomes energetically allowed.

Experimentally one finds that the threshold for the new 1865 MeV/c^2 particles occurs right in the region between the narrow and broad peaks! This is illustrated in Fig. 1 which shows the $K^{\mp}\pi^{\pm}$ mass spectrum at the ψ, ψ' for all data and $\sqrt{s}$ = 4.028 GeV. The charm model goes one step further, namely the properties of the new quarks, C, are completely predicted.[7] These properties were chosen so that the weak neutral current is strangeness conserving, in accordance with strong inhibition observed for the $K_L^o \to \mu^+\mu^-$ decay (BR ≅ 10^{-8}).

B. Detailed Comparison with a K^* on the One Hand and the Charm Model on the Other

(i) Threshold

For a new $K^*(1865)$ we also expect a threshold. But that is expected at ~ 2.360 GeV [$K^*(1865)$ + K] or even ~ 2.755 GeV [$K^*(1865) + K^*(890)$]. However the experimental threshold lies above 3.1 - 3.7 GeV (see Fig. 1). In the charm theory[7] a threshold is expected at $\sqrt{s} = 2M_D \cong 3.73$ GeV, corresponding to $e^+e^- \to D^o\bar{D}^o$.

(ii) Associated Production

For a new $K^*(1865)$ we expect associated production with K or perhaps with $K^*(890)$ but there is no known reason to expect $K^*(1865) + \overline{K^*}(1865)$ associated production. Experimentally we find that all observed events corresponding to the 1865 MeV/c^2 peak occur in associated production with either equal or higher mass objects. Figure 2 shows the experimental recoil mass spectrum in which we use the measured momentum of the $K\pi$ system together with the measured $K\pi$ invariant mass (2a) as well as a fixed mass (2b): the nominal value $M = 1865\ \mathrm{MeV}/c^2$.

(iii) The Charged Decay Mode

For a K^* with $I = 1/2$ we also expect a charged decay mode. For decays into three body this would have to be the nonexotic* mode $K^{\mp}\pi^{+}\pi^{-}$. Experimentally we observe the exotic decay mode $K^{\mp}\pi^{\pm}\pi^{\pm}$ and do not observe the nonexotic decay mode (see Fig. 3); neither do we observe the $I = 5/2$ triply-charged $K^{\mp}\pi^{\mp}\pi^{\mp}$ decay mode (not shown here). Thus if the peak corresponds to a K^* it must have $I = 3/2$; i.e., an exotic K^*, which (incidentally) would be the first clear case of an exotic meson state. If we adopt the point of view that we are dealing with an exotic K^*, we would still have to invent an explanation for the peculiar fact that the $I_z = \pm 1/2$ states (the nonexotic combinations $K^{\mp}\pi^{+}\pi^{-}$) are suppressed.

On the other hand our observations are in good agreement with charm theory in which Cabibbo-enhanced hadronic weak decays obey a $\Delta C = \Delta S$ rule, that is the charmed quark c decays weakly to $s\bar{d}u$. Thus in D^+ ($C = 1$, $S = 0$) decay, for example, the final state has $C = 0$, $S = -1$ together with $Q = +1$; i.e., the charged final state is predicted to be exotic. This point holds explicitly for the charm model and would not necessarily by true for other new types of mesons, M, composed of $\bar{q}Q$.

(iv) Experimental Width

For a K^* of mass $1865\ \mathrm{MeV}/c^2$ we might expect a width $\Gamma \approx 50-200\ \mathrm{MeV}/c^2$, although admittedly for an exotic K^* we have no clear prediction. Experimentally, we find $\Gamma < 40\ \mathrm{MeV}/c^2$ from the mass spectrum; however, by making use of the information from the recoil spectrum as well this limit becomes $\Gamma < 5\ \mathrm{MeV}/c^2$.

*Here exotic refers to the fact that the strangeness is opposite to the charge of the $K^{\mp}\pi^{\pm}\pi^{\pm}$ object, an impossibility for a quark-antiquark combination of the conventional three quarks.

Charm theory predicts that the decays we are dealing with are weak decays and estimates are: $\tau \sim 10^{-12}$ to 10^{-14} sec or roughly $\Gamma \sim 10^{-3}$ to 10^{-1} eV.

(v) Evidence for Parity Nonconservation or the "$\tau - \theta$ Puzzle" Revisited

For a K^* we expect parity conservation in the decay; this should hold even for an exotic K^*. Experimentally we find evidence for parity nonconservation. This is based on a study of the Dalitz plot for $K^{\mp}\pi^{\pm}\pi^{\pm}$ decay and the assumption that the charged and neutral states are I-spin multiplets. If parity is conserved in the $K^{\mp}\pi^{\pm}$ decay we must have the natural spin parity series $J^P = 0^+, 1^-, 2^+$, etc. For the $K^{\mp}\pi^{\pm}\pi^{\pm}$ decay mode: $J^P = 0^+$ is ruled out for three pseudoscalars in the final state by angular momentum and parity consideration. $J^P = 1^-, 2^+$, etc. give Dalitz plot distributions which vanish on the boundary. Our data rule this out clearly.[8] Thus we have strong evidence for parity nonconservation and hence a weak decay, consistent with the charm theory predictions.

(vi) Higher Mass States

For a $K^*(1865)$ there is no specific prediction for a next higher mass state. Experimentally we find from the recoil mass spectrum (see Fig. 2) a next higher mass state at ~ 2.006 GeV/c^2. From charm theory a state D^* is predicted with mass $M_{D^*} \sim 2$ GeV/c^2. If, without prejudicing the case, we use the nomenclature of charm theory, the observed four peaks in the recoil spectrum can be interpreted as:

$$e^+e^- \to D^o\overline{D}^o \quad (1)$$

$$\to D^o\overline{D}^{*o} \text{ and } \overline{D}^oD^{*o} \quad (2)$$

$$\to D^*\overline{D}^* \quad (3)$$

and possibly one or more states giving rise to a recoil mass peak near 2.43 GeV/c^2.

(vii) Spin

For a $K^*(1865)$ one might expect spin values of $J = 3-4$, although again for an exotic K^* all bets are off. Experimentally we do not have a unique spin measurement as yet. However an analysis of the events represented by reaction (2) above can rule out simultaneous spin assignments for the states at 1865 and 2006 respectively of 0 and 0 as well as 1 and 0, while the assignments 0 and 1 are consistent with the data.[9] Charm theory predicts $J^P = 0^-$ and 1^- for the D and D^* respectively.

C. Results from Other Experiments As Well As Measurements in Progress

(i) Lifetime

For a K^* the lifetime is that typical of strong interactions; viz., 10^{-23} - 10^{-24} sec. Experimentally, in the SLAC-LBL magnetic detector, we can measure mean deviations from the beam-beam interaction point down to 0.5 - 1 cm and for these heavy particles this corresponds to $\tau = 5 \times 10^{-11}$ to 10^{-10} sec. Charm theory predicts weak decay lifetimes in the 10^{-12} to 10^{-14} sec region which are thus out of the range of our present detector.

Emulsion measurements in cosmic rays[10] and more recently at Fermilab in neutrino beams[11] have observed neutral and charged decays occurring $\sim 10\mu$ - 200μ from the parent interaction. If these are interpreted as the same phenomena as the $K^\mp\pi^\pm$ and $K^\mp\pi^\pm\pi^\pm$ events discussed here, they are consistent with the lifetimes predicted from charm theory. Clearly more detailed measurements are needed to settle this point.

(ii) Semileptonic Decays

In the SLAC-LBL detector it is not technically feasible to identify the low momentum muons and electrons from semileptonic decays associated with identified decays of the 1865 MeV/c^2 state. On the other hand the DASP experiment[6] at DESY has identified electrons in multiprong events ($N > 3$) with a maximum signal observed in the $\sqrt{s} = 4.0 - 4.2$ GeV region. These electrons, which appear to have a threshold above the ψ', cannot be explained by conventional background effects or be due entirely to heavy leptons.[3] They have also observed $K^{\pm}e$ correlations which peak in the same $\sqrt{s}$ region.

Furthermore the PLUTO group at DESY have observed $K_S^o e$ correlations also peaked in the $\sqrt{s} = 4.05$ GeV region.

While nobody has yet seen a 1865 MeV/c^2 event in associate production with semileptonic $K^{\pm}e\nu$ or $K_S^o e\nu$ decays -- as predicted in the charm model -- the evidence appears rather good that the observations at DESY do represent such decays.

More detailed studies of these processes should be forthcoming in the future.

(iii) The Cabibbo Suppressed Decay Modes

The charm model also predicts a specific ratio between Cabibbo enhanced and forbidden decay modes. For example,

$$(D^o \to \pi^-\pi^+)/(D^o \to K^-\pi^+) = \tan^2\theta_c$$

where θ_c is the Cabibbo angle. An indication for the suppressed process has been observed yielding $6.5 \pm 4\%$ for the above ratio.[12] Much more data is needed to fully establish this and possible other Cabibbo suppressed decay modes. Clear establishment of a Cabibbo suppressed decay mode is again a characteristic requirement of charmed quarks.

(iv) The F-Meson

In addition to the D^o and D^+ the isodoublet of the charm model, which correspond to $\bar{u}c$ and $\bar{d}c$, an additional singlet $\bar{s}c$ is predicted. This object which has decay modes into two strange particles, $F^+ \to K^+K^-\pi^+$ for example, has not been experimentally observed as yet.

Such an observation is still needed to complete the picture and make an unambiguous identification of the charm model with the experimental observations.

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FIGURE CAPTIONS

Fig. 1. A composite of the $K\pi$ mass distribution for the ψ/J region, the ψ' region and the $E_{cm} = 3.9-4.6$ GeV region (all data) as well as the $E_{cm} = 4.028$ GeV data separately.

Fig. 2. (a) M_{recoil} distribution against the $K^{\mp}\pi^{\pm}$ signal as measured. (b) M_{recoil} distribution against the $K^{\mp}\pi^{\pm}$ signal, as well as the kinematic reflection signals "$\pi^+\pi^-$" and "$K\bar{K}$," for fixed $M_{K\pi} = 1865$ MeV/c^2. Each distribution is background subtracted, and represents "all data." It is noteworthy that the recoil sharpens up considerably when $M_{K\pi}$ is taken as a unique mass.

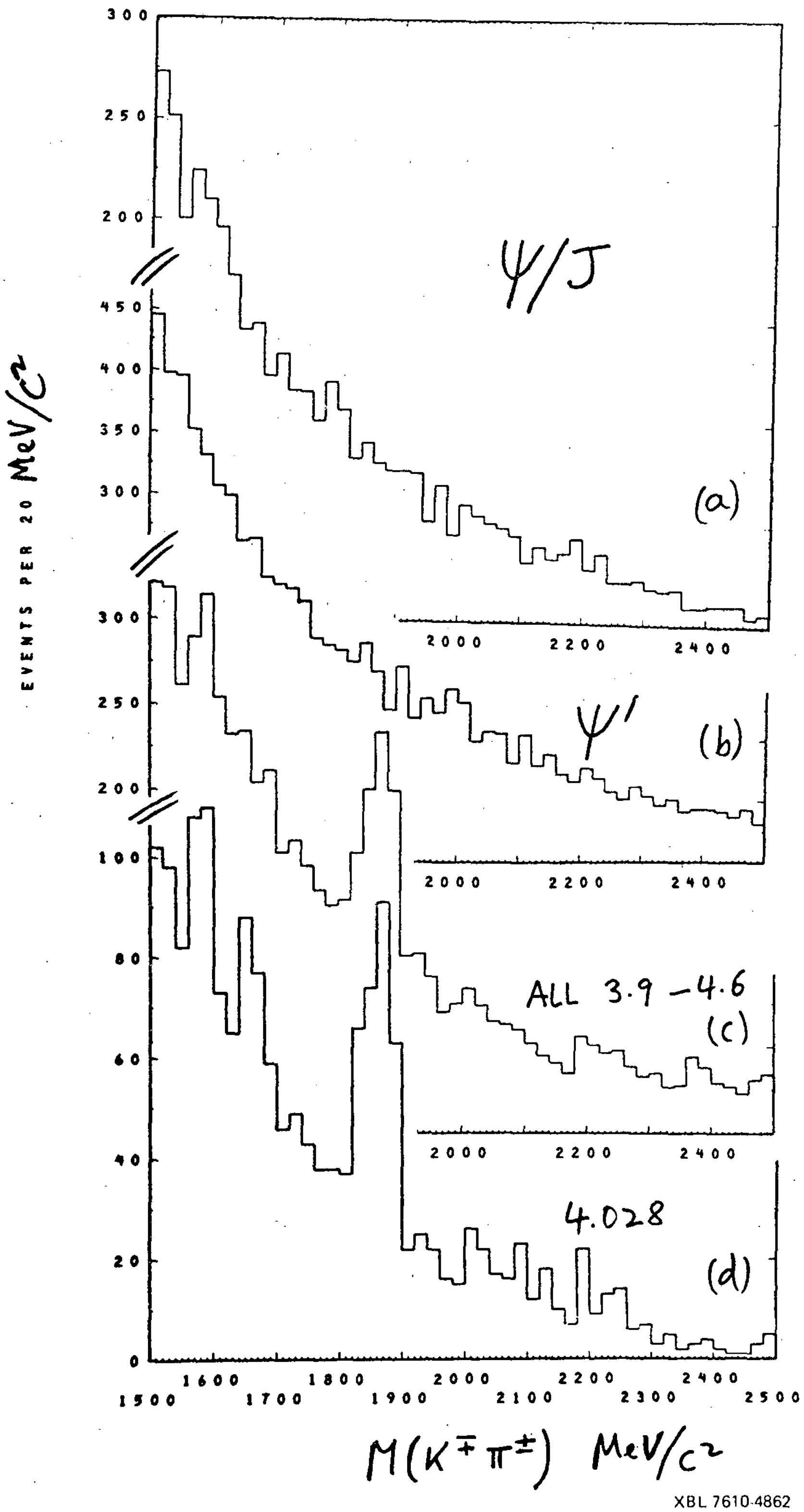
Ψ/J
(a)
Ψ'
(b)
ALL 3.9 –4.6
(c)
4.028
(d)
EVENTS PER 20 MeV/c²
M(K∓π±) MeV/c²
XBL 7610-4862

Fig. 1

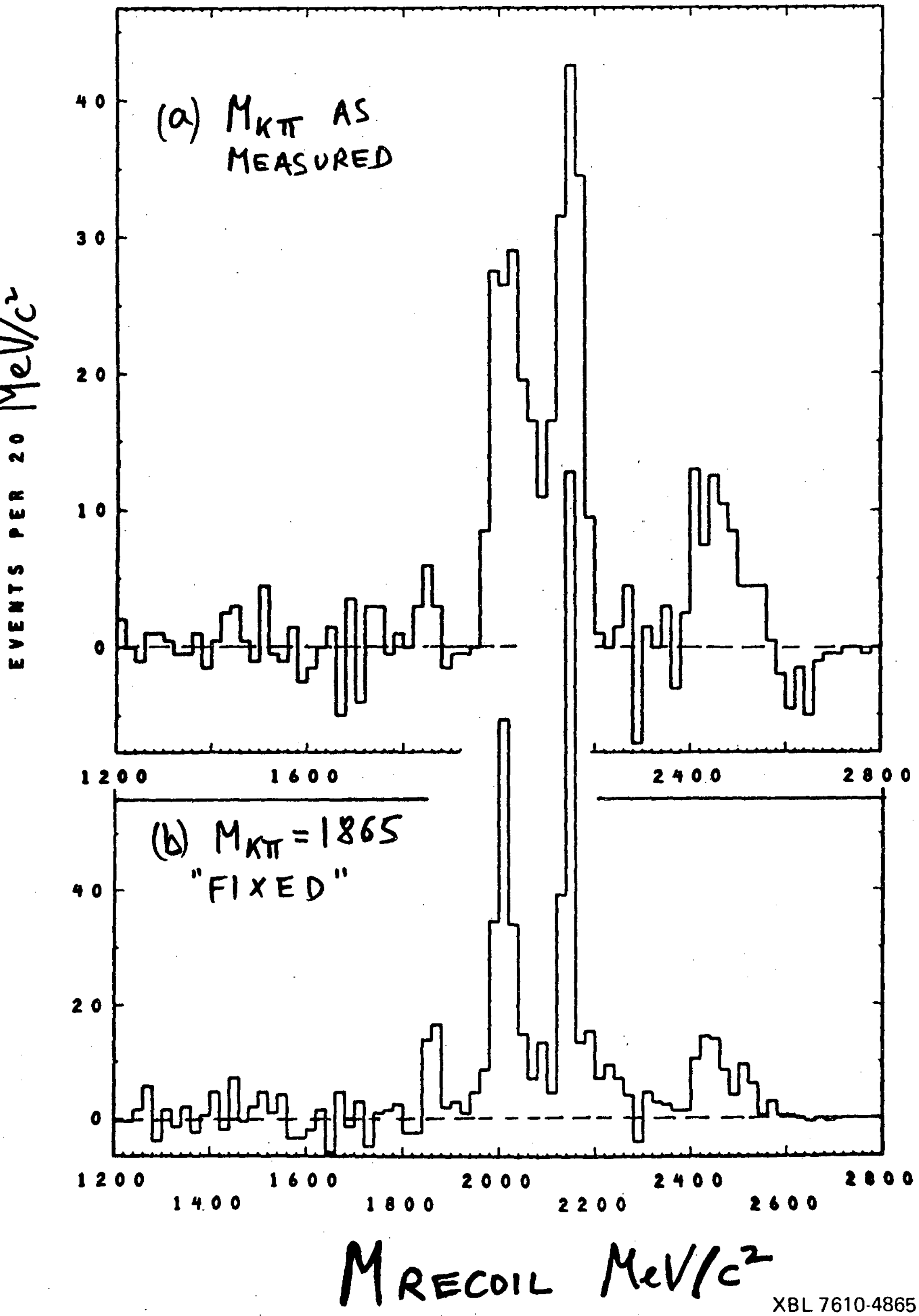
EVENTS PER 20 MeV/c²
(a) MKπ AS MEASURED
(b) MKπ = 1865 "FIXED"
40
30
20
10
0
1200
1400
1600
1800
2000
2200
2400
2600
2800
MRECOIL MeV/c²
XBL 7610-4865

Fig. 2

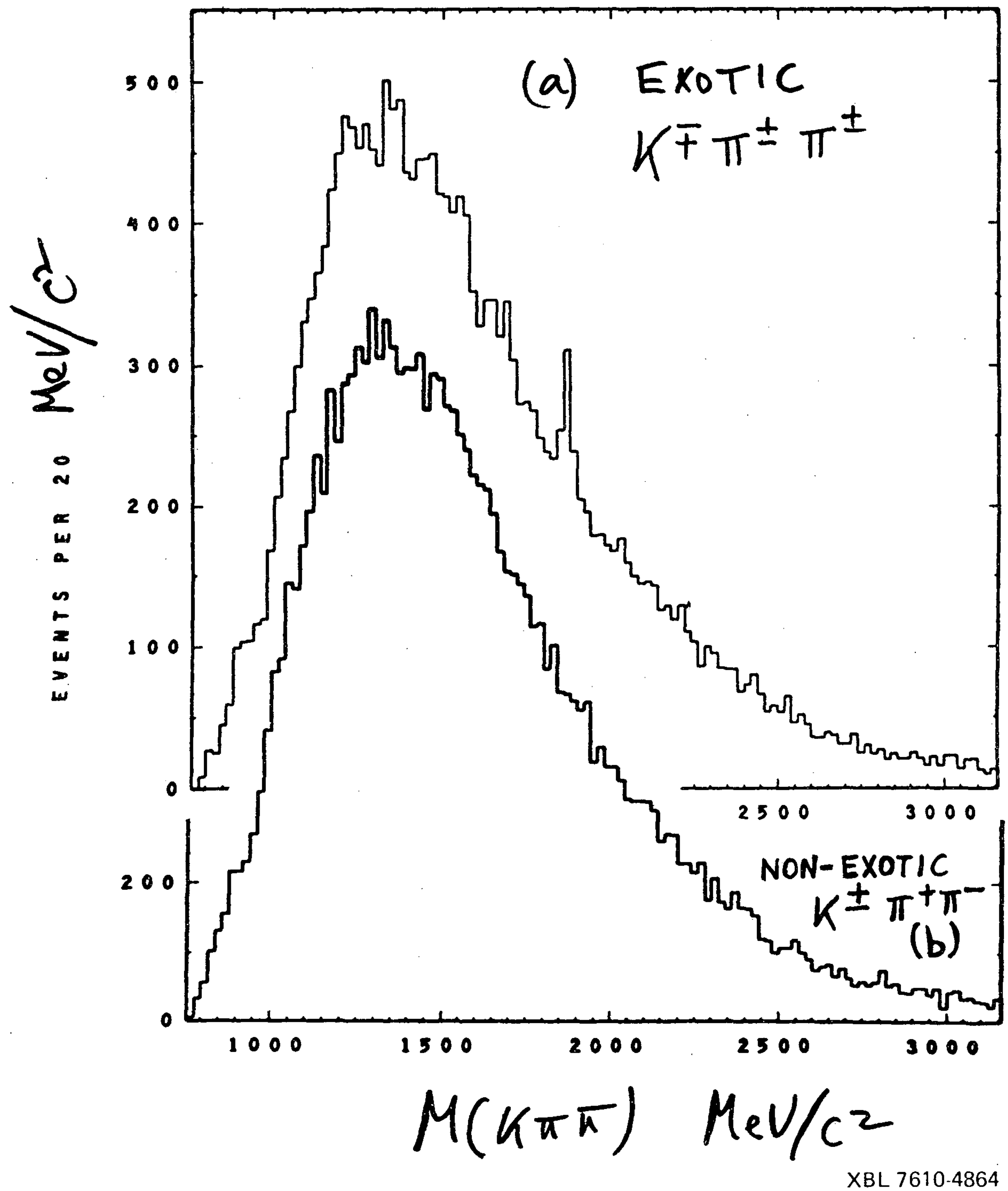
(a) EXOTIC
$K^{\mp}\pi^{\pm}\pi^{\pm}$
NON-EXOTIC
$K^{\pm}\pi^{+}\pi^{-}$
(b)
EVENTS PER 20 MeV/c²
M(Kππ) MeV/c²
500
400
300
200
100
0
200
0
1000
1500
2000
2500
3000
XBL 7610-4864

Fig. 3

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