ity too small by a factor of 16; and we must choose the interaction four times stronger than V_{TF} to fit the observed T^2 term.

For $1/\tau_{phon}$ we use

$$1/\tau_{phon} = (2\pi/\hbar)\lambda k_B T[4(T/\theta_R)^4 J_5(\theta_R/T)], \qquad (10)$$

where $\theta_R = 2p_F v_{sound}$ and J_5 is a Debye integral. Since our theory predicts that $\rho = A + BT + CT^2$ for stoichiometric TiS_2 at high T and the linear term is not evident experimentally, we conclude that the electron-phonon coupling constant is rather small ($\lambda \lesssim 0.05$), which we do not fully understand. $1/\tau_{imp}$ is now determined by the observed resistivity ratio of 10. [Our e-h analysis of experiment[8] shows that $1/\tau_{ip}$ is not the same for electrons and holes as assumed in Eq. (6) and that a straightforward generalization is required.]

Nonstoichiometric TiS_2 is obtained by intercalating additional Ti atoms, which are each assumed to give up four electrons. Calculating the electron and hole densities as functions of x in $Ti_{1+x}S_2$, we find that all the holes are filled when $n_e = 5.4n_0$ or $x = 0.015$. Using the same parameters as for stoichiometric TiS_2 and assuming further that $1/\tau_{ip}$ scales as the density of states, we are able to calculate the temperature-dependent resistivity of $Ti_{1+x}S_2$ for different values of x. We exhibit curves for $\lambda_e = \lambda_h = 0$ and 0.05 in Fig. 1, which has been discussed earlier.

In conclusion, we emphasize that the general features of our off-stoichiometry predictions are independent of our crude approximation to the e-h interaction; and, therefore, these experiments will provide a severe test of the theory. Obviously more work on the interaction is needed, but the additional effort will be justified only if experiments confirm that e-h scattering is the dominant mechanism. Thompson informs us that systematic measurements on nonstoichiometric samples are now underway and his preliminary results are in qualitative agreement with our predictions.

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COMMENTS

Charm Spectroscopy via Electron-Positron Annihilation*

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Electron-positron annihilation should be a rich source of charmed hadrons. The search for invariant-mass peaks together with the measurement of recoil-mass spectra is a technique that recently has borne fruit at SPEAR. We show how this technique may reveal the existence of the charmed baryons and of the excited states of the charmed mesons.

Charmed hadrons should be abundant in debris of e^-e^+ annihilation above the charm threshold.[1] A good candidate for the lightest charmed particle D^0 was found at SPEAR[2] at 1.865 GeV decaying into $K^-\pi^+$ and $K^-\pi^-\pi^+\pi^+$, presumably a $J^P = 0^-$ S-wave $c\bar{u}$ meson. Its isotopic partner D^+ must exist at a slightly higher mass and be less copiously produced.[3] The recoil-mass spectrum[2] against the observed D^0 indicates[3] the existence of a higher state at ~2.00 GeV, presumably the hyperfine partner D^*, which is an S-wave $J^P=1^-$ isodoublet. Both masses agree with the predictions.[4] Near the threshold ($\sqrt{s}=3.8-4.1$ GeV quasi-two-body final states involving D or D^* should dominate charm production. The observed recoil spectrum at these energies agrees with the predictions.[3] This work concerns the search for heavier charmed hadrons at higher $\sqrt{s}$.

In the $l\neq 0$ states of a c quark and a light antiquark, the principal spin-dependent force is the spin-orbit coupling of the light antiquark. The system resembles a hydrogen atom where the electron angular momentum is a useful quantum number, but not the total spin of the electron and proton. We have shown[5] that the particle eigenstates of P-wave excitations of D correspond approximately to states with definite $\vec{j}=\vec{l}+\vec{s}$, where $\vec{l}=1$ is the orbital angular momentum and $\vec{s}$ is the light antiquark spin: The four states correspond to the values $J_{2j}{}^P=2_3{}^+$, $1_3{}^+$, $1_1{}^+$, and $0_1{}^+$. From the analysis of Ref. 4, we estimate their masses to be 2.36, 2.33, 2.25, and 2.24 GeV, respectively.[6] All P-wave states of the D decay strongly: the 1^+ states, principally to $D\pi$; and the 2^+ and 0^+ states, to $D^*\pi$ [see Fig. 1(a)]. Their decay widths, estimated by comparison with analogous decays of familiar particles, are ~50 MeV.

The S-wave production by e^+e^- annihilation of one P-wave D and one S-wave $\bar{D}$ or $\bar{D}^*$.—A heavy $c\bar{c}$ pair is produced by the virtual photon, after which strong interactions produce a light $q\bar{q}=u\bar{u}$ or $d\bar{d}$ which combines with $c\bar{c}$ forming the two charmed mesons. Let $\vec{S}$, $\vec{S}'$, $\vec{s}$, $\vec{s}'$, and $\vec{l}$ denote the spins of c, $\bar{c}$, $\bar{q}$, and q and the orbital angular momentum of $c\bar{q}$, respectively. $\vec{S}+\vec{S}'$ and $\vec{s}+\vec{s}+\vec{l}$ are each conserved if one neglects the spin-spin couplings and spin-orbit couplings involving heavy quarks; moreover $(\vec{S}+\vec{S}')^2=2$ and $\vec{s}+\vec{s}'+\vec{l}=0$. Thus, $j^2=(\vec{s}+\vec{l})^2=\frac{3}{4}$; and the quasi-two-body production of the $2_3{}^+$ and $1_3{}^+$ states is forbidden in our approximation. The only allowed processes of the kind we consider are $e^+e^-\to D(1_1{}^+)\bar{D}^*$, $D(1_1{}^+)\bar{D}$, and $D(0_1{}^+)\bar{D}^*$. With neglect of the threshold and form-factor effects, these three reactions proceed in the ratios 2:1:1.

In Fig. 2 we show the expected recoil distributions agains the detected D^0's at energies where the production of charmed (nonstrange) mesons should be dominated by quasi-two-body production of one S-wave and one P-wave meson, or two S-wave mesons. We have argued that most D^*'s produce D^0's in their strong decays because of their electromagnetic mass splittings.[3] The same form factor is used as in Ref. 3, but the S-wave threshold factors are used wherever appropriate. A dimensional parameter relates the production of two S-wave mesons to the production of one S wave and one P wave: We take it to be 1 GeV. The recoil distributions are complicated since the detected D^0's can originate in ten different ways, as indicated in Fig. 2. A study of the evolution in energy of the recoil structure can reveal the P-wave charmed mesons, but is probably inadequate to prove the existence of the two states

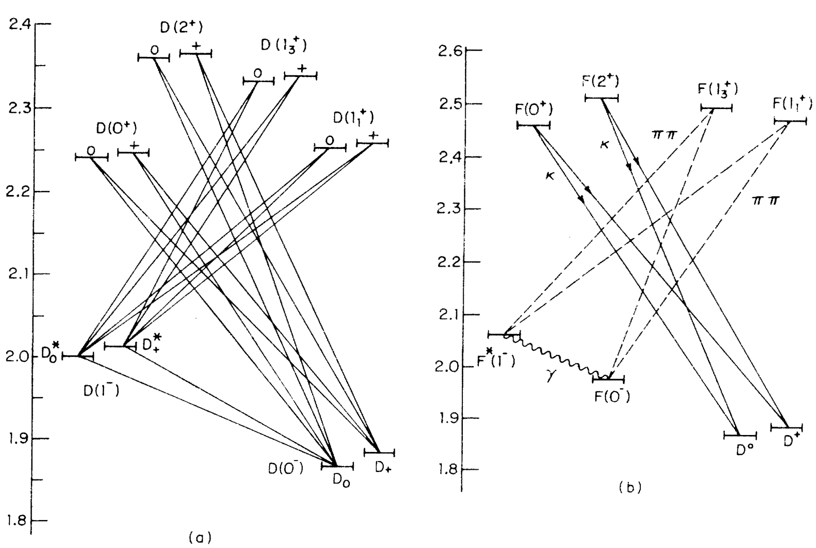

FIG. 1. Spectrum and the principal decays of (a) D mesons and (b) F mesons.

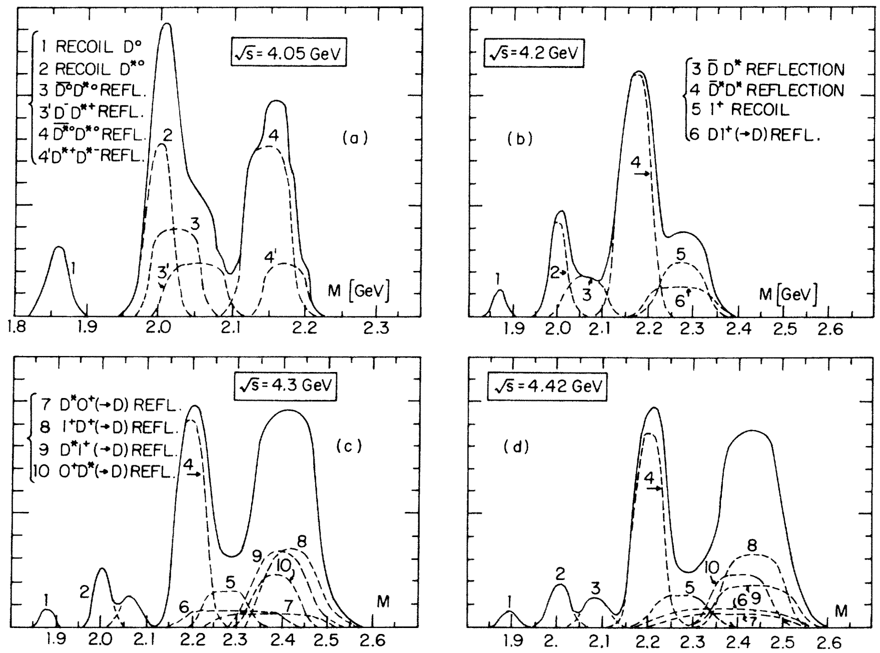

FIG. 2. Predicted recoil-mass spectra against the detected D^0 at several energies; 25-MeV resolution.

produced and to determine their masses. A cleaner approach involves the study of the recoil-mass distributions against the observed $D^{\pm}$, where there will be fewer kinematical reflections (but also fewer $D^{\pm}$'s).

There will be an analogous spectroscopy of quasi-two-body-produced $F = c\bar{s}$ involving the S-wave 0^- (1.975 GeV) and 1^- (2.06 GeV) F mesons, and the P-wave 0^+ (2.46 GeV) and 1^+ (2.465 GeV) F mesons. If our mass estimates are correct, the 1^- state F^* decays radiatively into the 0^- ground state F, the 1^+ state decays via the Zweig-Iizuka-suppressed two-pion emission to F or F^*, and the 0^+ state emits a kaon to become a 0^- D meson [see Fig. 1(b)]. Recoil-mass spectroscopy will be fruitful, but we must await the discovery of bumps in $K^+K^-\pi^{\pm}$, $K_sK_s\pi^{\pm}$, or $K_sK^{\pm}$.

Baryons.—Three reasons for a significant charmed-baryon yield are as follows: The charmed baryons are not much heavier than the charmed mesons so that there is no argument against their production because of their masses. The form factors governing the production of charmed hadrons are associated with the masses of the $J^P = 1^-$ $c\bar{c}$ states (3.1, 3.7, 4.1, and 4.4 GeV), but not with the ρ mass; thus, there is no argument against the charmed baryon production because of the small form factors. Lastly, the "smoothed" experimental value[7] of $R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ shown in Fig. 3 shows a clear shoulder very near the relevant charmed baryon thresholds, possibly indicating as much as a 5% production of the charmed baryons at $\sqrt{s} \sim 5$ GeV.

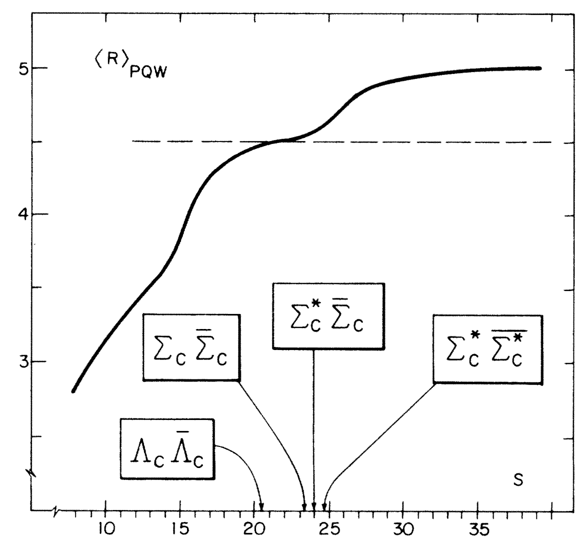

FIG. 3. Smoothed experimental value of R according to Ref. 7. Relevant charmed baryon thresholds are shown. We expect the $\Lambda_c\bar{\Lambda}_c$ threshold to be ~ 9 times less pronounced than the combined effect of the other three. The portion above the dotted line may be considered charmed baryon production.

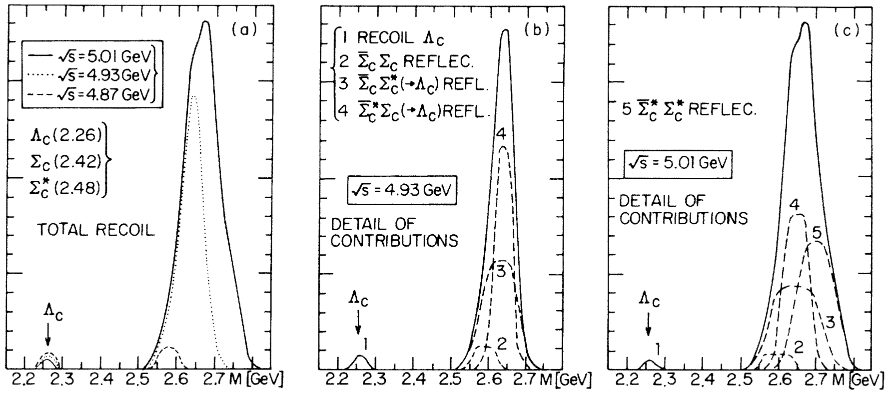

FIG. 4. Predicted recoil-mass spectra against the detected Λ_c^+ at several energies.

The expected S-wave, singly charmed, nonstrange baryons are Λ_c^+ with $J^P = \frac{1}{2}^+$, Σ_c^0, Σ_c^+, and Σ_c^{++} with $J^P=\frac{1}{2}^+$, and Σ_c^{*0}, Σ_c^{*+}, and Σ_c^{*++} with $J^P = \frac{3}{2}^+$. In Ref. 4 we computed a Σ_c-Λ_c mass splitting of 160 MeV and a Σ_c^*-Λ_c mass splitting of 220 MeV. The mass of Λ_c was predicted to lie between 2.2 and 2.3 GeV. A single bubble-chamber $\Delta S = -\Delta Q$ event[8] seems to involve the quasielastic production of Σ_c^{++} which decays to $\Lambda_c^+\pi^+$. Consistency with this observation requires us to put $m(\Lambda_c) = 2.26$ GeV, $m(\Sigma_c) = 2.42$ GeV, and $m(\Sigma_c^*) = 2.48$ GeV. Σ_c and Σ_c^* are expected to decay strongly into $\Lambda_c\pi^+$ with widths $\lesssim 10$ MeV.

Only Λ_c decays via the weak interactions. Among its two-body decays are the $\Lambda\pi^+$ and pK_s modes. We anticipate the discovery of a peak in the invariant mass of these particles and the corresponding antiparticles as well.

The S-wave production by e^+e^- annihilation of a pair of charmed baryons.—A heavy $c\bar{c}$ pair is produced by the virtual photon, after which strong interactions produce two light $q\bar{q}$ pairs which combine with $c\bar{c}$ forming two charmed baryons. Again, we neglect the spin-dependent couplings of the heavy quarks. To the extent that the spin-isospin SU(4) symmetry among the light quarks is applicable, we deduce that the pair production of the $I=0$ charmed baryons to the pair production of the $I=1$ charmed baryons is in the ratio of 1:9. The associated production of an $I=0$ and $I=1$ baryon is isotopically forbidden.

Let $\vec{s}_1$, $\vec{s}_1{}'$, and $\vec{S}_1$ denote the spins of the light quarks and c; and $\vec{s}_2$, $\vec{s}_2{}'$, and $\vec{S}_2$, the spins of the corresponding antiquarks. In our approximation, $\vec{s}_1 + \vec{s}_1{}' + \vec{s}_2 + \vec{s}_2{}' = 0$ and $(\vec{S}_1 + \vec{S}_2)^2 = 2$. Furthermore, the light and heavy quark spins are uncorrelated: $\langle \vec{s}_i \vec{S}_j\rangle = \langle \vec{s}_i{}' \vec{S}_j \rangle = 0$. From these facts, we deduce the relative production ratios (neglecting the threshold effects) of $\Lambda_c\bar{\Lambda}_c$, $\Sigma_c\bar{\Sigma}_c$, $\Sigma_c\bar{\Sigma}_c^* + \Sigma_c^*\bar{\Sigma}_c$, and $\Sigma_c^*\bar{\Sigma}_c^*$ to be 3:1:16:10.

Introducing an S-wave threshold factor and a form-factor $(S-M^2)^{-1}$, where $M = 4.4$ GeV is the nearest $J^P = 1^-$ $c\bar{c}$ state, we obtain the predicted recoil-mass distributions shown in Fig. 4. The conspicuous and rather broad bump is a confluence of four kinds of kinematical reflections. Note that it is displaced measurably upwards in energy as $\sqrt{s}$ is increased.

Many aspects of hadron spectroscopy remain to be explored in e^+e^- annihilations.

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