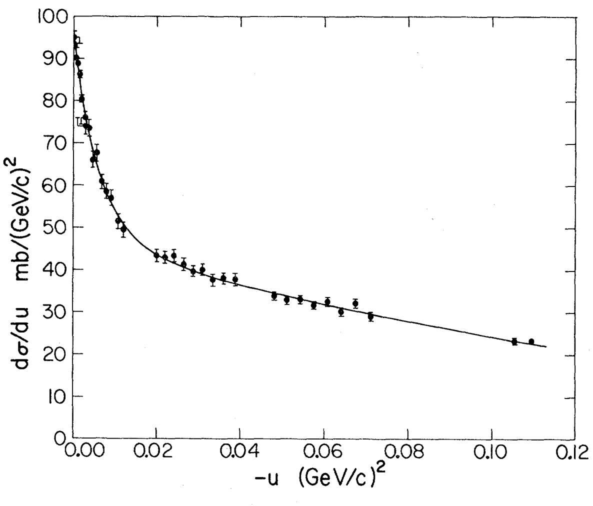

FIG. 3. Double exponential fit to $d\sigma/d\Omega$ values for present data.

In conclusion, we believe that the validity of our results is supported by the high degree of internal consistency in our data and the good value for the pion-nucleon coupling constant derived from the shape of the backward peak. This coupled with the excellent statistical accuracy and the large number of points should be of great value in obtaining a meaningful phase-shift analysis for n-p scattering at this energy.

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Interplay of Confinement and Decay in the Spectrum of Charmonium*

E. Eichten,† K. Gottfried, T. Kinoshita, K. D. Lane, and T.-M. Yan‡
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14853
(Received 25 November 1975)

The spectrum of charmonium in the presence of a charmed-meson continuum is investigated. Radiative rates are in considerably better agreement with data than for the naive model, the largest discrepancy being a factor 2–3 for $\psi' \to \gamma + {}^3P_0$. The model accounts for the peak at ~ 4.2 GeV in $\sigma(e\bar{e} \to \text{had})$, and predicts a further peak at ~ 3.75 GeV due to 1^3D_1. The latter would be the most favorable location for a charm search in $e\bar{e}$ collisions.

The interpretation[1] of the ψ resonances as bound states of charmed quark pairs ($c\bar{c}$) has enjoyed considerable success. In particular, the prediction[2-4] that P states lie between ψ and ψ' may be confirmed by recent observations,[5,6] and the expected ^1S ground state η_c may also have been discovered.[7] Nevertheless, the naive model must be modified substantially near and above the charm threshold W_c due to coupling to decay channels. We have generalized the model to incorporate such effects.[8] Our method provides a comprehensive approach to the interplay between confinement and decay in meson spectroscopy.

Before reporting our results,[9] we must come to grips with two aspects of the data that could be in conflict with the model's basic assumptions:

(I) $R \equiv \sigma(e\bar{e} \to \text{had})/\sigma(e\bar{e} \to \mu\bar{\mu})$ has an observed asymptote[10] of $\simeq 5.5$ which greatly exceeds the theoretical value of $3\frac{1}{3}$. This would pose a serious problem were it not for the indication[11] that there is a new leptonic threshold below 4 GeV. We accept this interpretation of the data, and assume that the remaining discrepancy between ≈ 4.5 and $3\frac{1}{3}$ can be ascribed to the corrections to asymptotic freedom.

(II) The ψ-η_c splitting appears to be[7] $\simeq 300$ MeV, which is much larger than the original estimate,[1] and the splitting of the intermediate χ multiplet is also large.[6] Can these facts be accommodated by the corrections to the nonrelativistic model? A re-examination[12] of this question with our potential[3] yields a ψ-η_c splitting of 120–160 MeV, and P-state splittings of 100–150 MeV, the latter in adequate agreement with the observed[6] $\chi(3.51)$-$\chi(3.41)$ interval. Qualitative consistency with the model can therefore be attained by assigning[13] the natural spin-parity state $\chi(3.41)$ to $^3P_0$, and $\chi(3.51)$ to $^3P_1$; $^3P_2$ would then be expected at $\simeq 3.6$ GeV, above any of the χ's presently seen, while $\chi(3.53)$ would be assigned to 2^1S $(=\eta_c')$. Another possibility is that $\chi(3.53)$ contains both $^3P_2$ and η_c'; this is favored by a comparison of the data with our decay rates (see Table II), but it is inconsistent with existing models of the spin forces.

We now turn to those problems to which the present work is addressed: (A) The electromagnetic decays of ψ' do not agree with the original estimates[3]: The observed strengths[5,6,14,15] for $\psi' \to \gamma\chi$ are several times smaller than predicted, and[16] $\Gamma_e(\psi') = 2.1 \pm 0.3$ keV, in contrast to the theoretical value of 3.0–3.4 keV. (B) The naive model has further $^3S_1$ (and $^3D_1$) states that obviously lie above the threshold W_c. One of these, 3^3S_1, is presumably the broad peak[17] in R at $\simeq 4.1$ GeV. But as it stands, the model does not handle the decay of such states, nor the structure of cross sections above W_c.

As ψ' appears to be very close to W_c, it may also be unrealistic to describe it as a pure $c\bar{c}$ state; problems (A) and (B) therefore require a unified treatment.

For this purpose we propose a unified model of confinement and decay based on a universal *instantaneous* interaction between quark color densities ρ_a:

$$H_I = -\tfrac{1}{2}\int d^3r\, d^3r' \sum_{a=1}^{8} :\rho_a(\vec{r})U(\vec{r}-\vec{r}\,')\rho_a(\vec{r}\,'):.$$

Here $U = 4r/3a^2$ is the linear[18] potential of the naive model. Hopefully H_I simulates the interaction due to a colored gauge field.

When the quark fields in ρ_a are decomposed into destruction and creation operators, H_I separates into a variety of terms. The one in the $c\bar{c}$ sector gives the naive charmonium spectrum, while that in the[19] $c\bar{q}$ sector binds the charmed mesons D, F, etc. There is also a term linking the $c\bar{c}$ and $(c\bar{q}, \bar{c}q)$ sectors, which gives the decay amplitudes allowed by the Okubo-Zweig-Iizuka rule. Thus the bound states and decay amplitudes are, in principle, determined by a single interaction.[20] Since decay leads to level shifts, the parameters m_c and a have to be readjusted by fitting to the ψ-ψ' mass difference, and $\Gamma_e(\psi)$.

All quantities of interest can be extracted from the resolvent $\mathcal{G}(z) = P_\psi(z-H)^{-1}P_\psi$, where P_ψ projects onto the $c\bar{c}$ sector. Thus $\mathrm{Im}\langle r=0|\mathcal{G}(W+i0) \times |r=0\rangle$ gives the probability of finding a $c\bar{c}$ pair at zero separation, and hence the contribution δR of charm to R. The poles of $\mathcal{G}$ below W_c locate the bound states, and their residues locate the wave functions as modified by virtual decay. From $\mathcal{G}$ one can easily compute amplitudes for processes such as $D\bar{D} \to F\bar{F}$ or $e\bar{e} \to D\bar{D}$.

We first evaluate $\mathcal{G}$ in the 1^{--} sector by the following steps: (a) reduction of terms in H_I to their nonrelativistic limits; (b) evaluation of eigenvalues and eigenfunctions in a $c\bar{c}$ subspace $\mathcal{K}_\psi$ with input parameters a and m_c; (c) evaluation of the Zweig-allowed[21] decay amplitudes $\mathcal{W} = P_C H_I P_\psi$, where P_C projects onto a subspace $\mathcal{K}_C$ of the $(c\bar{q}, \bar{c}q)$ sector; we take $\mathcal{K}_C$ to contain all combinations of D, D^*, F, F^*; (d) solution of

$$\mathcal{G} = G_\psi + G_\psi \mathcal{W}^\dagger G_C \mathcal{W}\mathcal{G},$$

where[22] $G_\alpha = (z - P_\alpha H P_\alpha)^{-1}$; (e) readjustment of m_c and a; (f) enlargement of $\mathcal{K}_\psi$ until $\mathcal{G}$ stabilizes in the energy regime of interest. Having solved the 1^{--} sector, we then use the same parameters[23] to evaluate $\mathcal{G}$ in the ^3P_J sectors.

The replacement of a complete set of $(c\bar{q}, \bar{c}q)$ states by the subspace $\mathcal{K}_C$ is an increasingly dubious approximation as the energy rises. It is also unlikely that dynamic relativistic effects can be ignored in the decay sector, even if they

TABLE I. Modification of states due to decay. The numbers listed under the various states give their norms in the $c\bar{c}$ sector.

W_c (GeV)	$^3P_0$	$^3P_1$	$^3P_2$	2^3S_1	$\Gamma_e(\psi')$ (keV)
3.70	0.68	0.75	0.79	0.58	3.6
3.75	0.71	0.76	0.79	0.67	4.1

are only of secondary importance in the $c\bar{c}$ sector. For these reasons our calculations can only be trustworthy for relatively low energies, hopefully $W \lesssim 4.6$ GeV.

In brief, our principal results are these:

(1) Although energy shifts due to virtual decay are quite large,[23] the "renormalized" bound state spectrum does not differ markedly from that of the naive model. In particular, the ^3P center of gravity is at 3.44 GeV. P-state splittings due to virtual decay[18] are only $\simeq 15$ MeV.

(2) The states $|^3P_J\rangle$ and $|\psi'\rangle$ are strongly modified by virtual decay, but this effect is not sensitive to the threshold (see Table I).

(3) The modification of ψ' does not produce the desired reduction of $\Gamma_e(\psi')$ to 2.1 ± 0.3 keV (see Table I).

(4) Calculated $E1$ rates are given in Table II. Decay effects strongly suppress some strengths

TABLE II. Radiative transitions. We set $W_c = 3.70$ GeV. If $W_c = 3.75$ GeV, then $\Gamma_0 = 28$ keV, $\Gamma_1 = 14$ keV, and $\Gamma_2 = 18$ or 3 keV.

	$E1$ transitions[a,b]		
$\psi' \to {}^3P_J$	$J=0$	$J=1$	$J=2$
$A_{c\bar{c}}$	1.04	1.04	1.04
$A_{\rm decay}$	0.78	0.39	0.39
$A_{\rm pair}$	−0.12	−0.05	−0.11
$S \times 10^6$	1.93	1.98	4.46
S/S_0	0.92	0.31	0.42
Γ_J	36 keV	9.7 keV	15 or 2.6 keV[c]
	$M1$ transitions[d]		
	$\psi \to \eta_c$	$\psi' \to \eta_c$	$\psi' \to \eta_c'$
Γ	22 keV	10 keV	2 keV

[a] $A_{c\bar{c}}$, $A_{\rm decay}$, and $A_{\rm pair}$ are $2^3S_1 \to 2^3P_J$ amplitudes in the $c\bar{c}$ sector, that in the decay sector, and that due to the pair creation term in the current. S is the total strength in GeV^{-2}; it also includes mixing of different S, P, and D states. S_0 is the strength in the naive model.

[b] $\Gamma(^3P_J \to \psi\gamma) = 90$, 230, and 280 keV for $J = 0, 1, 2$, with $M(^3P_2) = 3.53$ GeV.

[c] Γ_2 for $M(^3P_2) = 3.53$ or 3.60 GeV, respectively.

[d] Assumed masses for η_c and η_c' are 2.80 and 3.53 GeV.

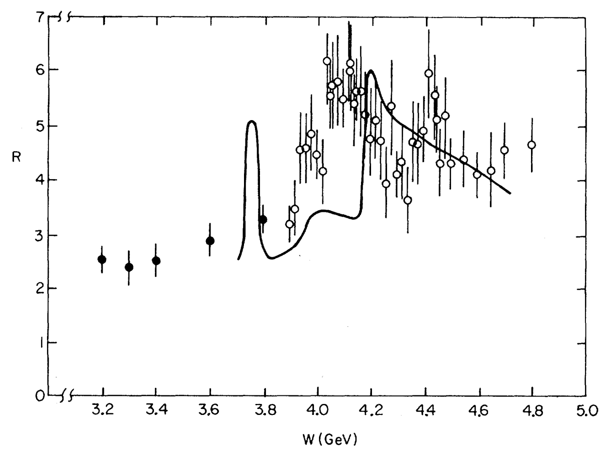

FIG. 1. R above the charm threshold, taken as $W_c = 3.70$ GeV. A "background" of 2.5 for noncharmed final states is included. The peak at 3.75 GeV is a $^3D_1$ resonance, that at 4.2 GeV is 3^3S_1. Solid points are from Ref. 17, open points preliminary data from Ref. 10.

(see S/S_0). $E1$ rates are in good agreement with present experimental indications for transitions to $^3P_2$ and $^3P_1$, and a factor of ~2–3 too large for $^3P_0$. (Even in atomic physics it is difficult to compute $E1$ strengths quantitatively.[24])

(5) Because of virtual decay, the radial $1S$ and $2S$ $c\bar{c}$ wave functions are not exactly orthogonal, and the suppression[3] of $\psi' \to \gamma\eta_c$ is no longer so drastic. Our rate for $\psi \to \gamma\eta_c$ is somewhat too large (see Table II).

(6) R is shown in Fig. 1. The peak at ~3.75 GeV is the first $^3D_1$ state already predicted in Ref. 3. Its precise location, width, and area are sensitive to the threshold and the spin-dependent forces.[12,18] To our knowledge, such a peak is not ruled out by the present data. The prominent peak at ~4.2 GeV is 3^3S_1. There is also a sharp D resonance at ~4.6 GeV (see Fig. 2); it is not revealed in R because in this region our decay amplitudes produce large interference effects with neighboring levels. The peak at ~4.2 GeV and the $^3D_1(4.6)$ resonance will shift downwards if further charmed thresholds are included ($\mathcal{H}_C$ is enlarged); this may also provide stronger e^+e^- coupling to the second $^3D_1$ resonance. Clearly the observed peak at ~4.1 is 3^3S_1; presumably the peak at ~4.4 GeV is the second D resonance.

(7) The most favorable reaction for finding charm at a storage ring is $e\bar{e} \to D\bar{D}$. Our calculations show that this process is unimportant except near threshold; for example, the 4.1 resonance decays mainly ($\gtrsim \frac{2}{3}$) into $D^*\bar{D}^*$. It is therefore important to search for the $^3D_1$ resonance

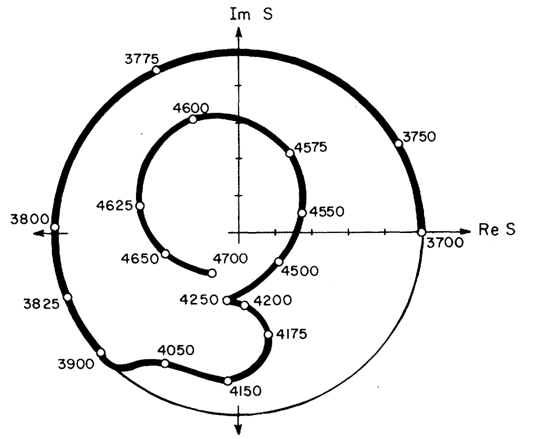

FIG. 2. The 1^{--} $D\bar{D}$ S matrix. The resonances at ~3.775 and ~4.175 GeV are the $^3D_1$ and $^3S_1$ states of Fig. 1. The inelastic resonance at ~4.60 GeV is a $^3D_1$ state that does not appear in R because of interference with other levels.

shown in Fig. 1 as it would provide a copious source of slow $D\bar{D}$ pairs.

Given our ignorance about charmed particles and the spin-dependent forces, one cannot expect quantitative agreement with the data. We therefore view these results as encouraging. They show that by incorporating decay effects one attains a greatly improved rendition of the data, and a first understanding of the dynamics and composition of charmed final states.

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†Present address: Institute for Advanced Study, Princeton, N. J. 08540.

‡Alfred P. Sloan Foundation Fellow.

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[13]Another argument for assigning 1^{++} to $\chi(3.51)$ rests on the fact that 1^{++} (in contrast to 0^{++} or 2^{++}) cannot undergo direct hadronic decay by annihilation into two identical massless gluons. Hence 1^{++} must decay into three gluons, and should have a considerably smaller hadronic width than 0^{++} or 2^{++}. Given our roughly equal population rates for the χ_J, we identify χ_1 as the state with the largest combined branching ratio for $\psi' \to \gamma\chi_J \to \gamma\gamma\psi$.

[14]As in atomic and nuclear spectroscopy, one should compare dipole strengths ($\equiv$ rate/k^3), not rates. Much of the discrepancy between the original predictions (Ref. 3) and the data is removed if measured γ energies k are used.

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[18]Our decay calculations ignore the small Coulombic term of Ref. 3, and all spin-dependent interactions.

[19]The (uds) quarks are collectively called q.

[20]In our calculations the masses of charmed mesons are extra parameters, however, but their wave functions belong to the potential U.

[21]By combining Zweig-allowed amplitudes one connects the $c\bar{c}$ and $q\bar{q}$ sectors. (We thank H. J. Lipkin and C. Schmid for bringing this point to our attention.) We estimate the ψ-φ mixing angle as $\sim 10^{-2}$, and that $\Gamma(\psi \to \text{had})$ is roughly of order 10 keV.

[22]Final-state interactions hardly influence R and are discarded.

[23]These are m_c, m_q, a, and the masses of the 0^- and 1^- charmed mesons. Our results are obtained with $m_c = 1.89$, $m_u = 0.31$, $m_s = 0.41$, $a = 1.57$. The "bare" 1^{--} masses in $\mathcal{H}_\psi$ are 3.28, 4.05, 4.70, and 5.29 for S states, and 4.12 and 4.73 for D states. (All numbers in GeV or GeV^{-1}.) For $W \lesssim 4.7$, $\mathcal{G}$ is insensitive to an enlargement of this $\mathcal{H}_\psi$. Masses in $\mathcal{H}_C$ are $M_D = 1.85$, $M_{D^*} = 2.08$, $M_F = 2.08$, and $M_{F^*} = 2.15$.

[24]For the lighter atoms with one valence electron, single-particle-model $E1$ strengths disagree with data by 20–50% [cf. W. L. Wiese, M. W. Smith, and B. M. Miles, *Atomic Transition Probabilities*, U. S. National Bureau of Standards, National Standards Reference Data Series—22 (U.S. GPO, Washington, D. C. 1969)].

Features of Diffraction Dissociation of Neutrons in *np* Collisions at 50–300 GeV/*c**

J. Biel, E. Bleser, T. Ferbel, D. Freytag, B. Gobbi, L. Kenah, J. Rosen, R. Ruchti, P. Slattery, and D. Underwood

University of Rochester, Rochester, New York 14627, and Fermi National Accelerator Laboratory, Batavia, Illinois 60510, and Stanford Linear Accelerator Center, Stanford, California 94305, and Northwestern University, Evanston, Illinois 60201

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We present preliminary results from an investigation of the reaction $n+p \to (p\pi^-)+p$ for neutron momenta in the range of 50 to 300 GeV/c. The data display a strong correlation between the mass of the $p\pi^-$ system and the four-momentum transferred in the production. Cross sections for producing low-mass $(p\pi^-)$ systems are independent of energy to within 10% accuracy.

We have measured the dissociation of neutrons into $(p\pi^-)$ systems using a variety of nuclear targets ranging from hydrogen to uranium. The data are from an experiment performed in the 1-mrad M-3 neutral-beam line of the Fermi National Accelerator Laboratory. In this Letter we will discuss the properties of the dissociation process as observed using a hydrogen target. We report, in particular, on the reaction

$$n+p \to (p\pi^-)+p \qquad (1)$$

for neutron momenta between 50 and 300 GeV/c.[1]

A schematic diagram of the apparatus is given in Fig. 1(a). The hydrogen target consists of a cylindrical high-pressure vessel. (Data were taken at operating gas pressures of 750 and 1250 lb/in.^{2}) The active target region is 20 in. in length and 3.5 in. in diameter; it is defined by a thin veto counter (A_1) at the upstream end, by a downstream counter (S), and by a set of sixteen plastic scintillator strips, each 20 in. long, $\frac{1}{4}$ in. thick, and $\frac{11}{16}$ in. wide, positioned azimuthally about the active region at a distance of $1\frac{3}{4}$ in. from the beam axis [see Fig. 1(b)]. All of the scintillators are contained within the high-pressure volume and are connected optically through acrylic light pipes to photomultiplier tubes located outside of the high-pressure vessel.[2] Photomultiplier signals from both ends of each of the sixteen azimuthal scintillator strips are pulse-height analyzed and this information is used off line to calculate the spatial location of the interaction vertex point, as well as to obtain a measure of the energy of the recoil proton in Reaction (1). A total of thirty spark chamber planes, read out magnetostrictively at both ends of each of the planes, provided substantial redundancy checks for background rejection; the effective spatial resolution of the chambers was ±0.3 mm.

Trigger requirements were designed to strongly favor Reaction (1) and to suppress multiparticle production processes. The trigger was satisfied under the following conditions: (1) no charged particle entered the target region (A_1 counter); (2) only one of the sixteen azimuthal scintillation counters surrounding the target region had a signal; (3) at least one charged particle emerged from the sensitive region of the hydrogen target, activating the S counter; (4) no charged (or converted neutral) particle was detected in any of the lead-scintillator–sandwich anticoincidence counters located downstream of the target, and positioned so as to shadow the area surrounding the magnet aperture; and (5) two of the six H_1 hodoscope elements immediately downstream of the magnet were activated.

A typical run consisted of 20 000 triggers taken over an 8 h period. Periodic runs were also taken with an empty target. A DEC PDP-15 computer was used to monitor the performance of the apparatus and to transfer data to magnetic tape for off-line analysis. A total of ~400 000 triggers were collected in the experiment; the data from about half of these will be presented in this report.

Spatial reconstruction, performed off line, provided vector-momentum information for the two charged tracks of the $(p\pi^-)$ "V" entering the mag-