rainbows suggests that there could be an intimate connection between the physics responsible for rainbows and the physics implicitly contained within our Franck-Condon factors.

In summary we have presented a model for a hindered diatomic-molecule rotor, worked out its quantum mechanics, and applied the results to a model dynamics problem involving a sudden release of the hindering potential. Conversion of zero-point kinetic energy into free rotational energy results in highly nonequilibrium final rotational-state distributions which have a striking resemblance to state distributions observed in several recent experiments involving different, but related, dynamic surface processes.

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[1] A. W. Kleyn, A. C. Luntz, and D. J. Auerbach, Phys. Rev. Lett. 47, 1169 (1981).

[2] R. R. Cavanagh and D. S. King, Phys. Rev. Lett. 47, 1829 (1981).

[3] L. Efstathiou and E. W. Thomas, in Proceedings of the Forty-Second Physical Electronics Conference, 1982 (to be published).

[4] D. White and E. N. Lassettre, J. Chem. Phys. 32, 72 (1960).

[5] I. F. Silvera and M. Nielsen, Phys. Rev. Lett. 37, 1275 (1976); I. F. Silvera, Rev. Mod. Phys. 52, 393 (1980).

[6] *Higher Transcendental Functions*, edited by A. Erdelyi (McGraw-Hill, New York, 1953), Vol. 1.

[7] J. D. Levine, Phys. Rev. 140, A586 (1965); J. W. Gadzuk, Phys. Rev. 154, 662 (1967).

[8] R. B. Bernstein and K. H. Kramer, J. Chem. Phys. 44, 4473 (1964).

[9] R. Schinke, J. Chem. Phys. 76, 2352 (1982), and references therein.

D^{*+} Production in e^+e^- Annihilation at 29 GeV

J. M. Yelton, G. J. Feldman, G. Goldhaber, G. S. Abrams, D. Amidei, A. Bäcker,(a) C. A. Blocker, A. Blondel,(b) A. M. Boyarski, M. Breidenbach, D. L. Burke, W. Chinowsky, G. von Dardel,(c) W. E. Dieterle, J. B. Dillon, J. Dorenbosch,(d) J. M. Dorfan, M. W. Eaton, M. E. B. Franklin, G. Gidal, L. Gladney, L. J. Golding, G. Hanson, R. J. Hollebeek, W. R. Innes, J. A. Jaros, A. D. Johnson, J. A. Kadyk, A. J. Lankford, R. R. Larsen, B. LeClaire, M. Levi, N. Lockyer, B. Löhr,(e) V. Lüth, C. Matteuzzi, M. E. Nelson, J. F. Patrick, M. L. Perl, B. Richter, A. Roussarie,(f) T. Schaad, H. M. Schellman, D. Schlatter, R. F. Schwitters, J. L. Siegrist, J. Strait, G. H. Trilling, R. A. Vidal, Y. Wang,(g) J. M. Weiss, M. Werlen,(h) C. Zaiser, and G. Zhao(g)

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, and Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720, and Department of Physics, Harvard University, Cambridge, Massachusetts 02138

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The production of the charmed meson state D^{*+} has been observed in e^+e^- annihilation at 29 GeV. The fragmentation function for charmed quarks appears to be peaked about $z = 0.5$.

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In the quark-parton model, quarks produced in high-energy reactions cannot emerge as free entities but materialize as jets of hadronic particles. The quark fragmentation functions describe the dynamical mechanism of the hadronization of quarks into hadrons. The heavy-quark fragmentation functions are of both theoretical and practical interest, but little is known of them. The production of charmed mesons in e^+e^- annihilation provides a clean way for studying the charmed fragmentation function.[1] Previous measurements of the differential cross section $d\sigma/dz$ for inclusive D meson production, where z is the ratio of twice the D energy (E_D) to the center-of-mass energy ($E_{\text{c.m.}}$), were restricted to the kinematic range of $z > 0.54$ available at SPEAR energies.[2,3] Here we present the observation of the D^{*+} by its decay

$$\begin{array}{l} D^{*+} \to D^0\pi^+ \\ \qquad\ \ \llcorner\!\!\to K^-\pi^+ \end{array}$$

and a measurement of the inclusive energy spectrum for D^{*+} production in e^+e^- annihilation at an energy of 29 GeV. (To avoid cumbersome notation, reference to a state will always imply the sum of that state and its charge-conjugate state.)

The data presented here were collected with the MARK-II detector at the PEP storage ring at the Stanford Linear Accelerator Center, and correspond to an integrated luminosity of 15.4 pb^{-1}. The D^{*+} candidates were found in a sample of roughly 5000 hadronic events. The MARK-II detector at PEP is substantially the same as that at SPEAR.[4] Charged-particle momenta were measured by using a 16-layer drift chamber in a 4.6-kG axial magnetic field. The charged-particle rms momentum resolution was $(\delta p/p)^2 = (0.015)^2 + (0.006p)^2$ (p in GeV/c), when tracks were constrained to come from the interaction region. Outside the drift chamber, time-of-flight (TOF) scintillation counters provided an rms timing resolution of 360 ps for hadron tracks, somewhat degraded from the value of 315 ps at SPEAR because of decreased scintillator attenuation length. This resolution made possible a π-K separation of greater than 1σ time difference for tracks with a momentum $p < 1.2$ GeV/c.

The TOF information was insufficient to assign unambiguous particle identities to most tracks. The tracks were designated pions, kaons, and protons if their measured TOF was within 580 ps of their calculated TOF; multiple identities were allowed. If the measured TOF was outside these limits, the particle was assumed to be a pion. If the TOF scintillation counter was crossed by more than one track, or for some other reason was unusable, the particle was tried both as a kaon and as a pion.

The invariant mass of all $K^-\pi^+$ combinations is shown in Fig. 1, split into two bands of $z = 2E_D/E_{\text{c.m.}}$. Although there is no statistically significant peak around the mass of the D^0 (1.863 GeV/c^2), mass combinations in the region $1.80 < M_{K\pi} < 1.93$ GeV/c^2 were taken as D^0 candidates. The two tracks were kinematically fitted to the D^0 mass, and those with a poor χ^2 rejected. The D^0 candidates were then each combined with an additional pion candidate of opposite-sign charge to the kaon candidate. The $D^0\pi^+$-D^0 mass difference spectrum is shown in Fig. 2 for the two bands of $z = 2E_{D^*}/E_{\text{c.m.}}$. At a center-of-mass energy of 29 GeV the kinematic range available for D^{*+} production is $0.14 < z < 1.0$. As the Q value of the decay $D^{*+} \to D^0\pi^+$ is very small, the momenta of the D^0 and π^+ in the laboratory frame will be approximately proportional to their masses. The drift chamber had low efficiency for detecting charged particles with momenta less than 100 MeV/c, so that the D^{*+} could not be readily detected for low values of z, and no measurement was possible for $z < 0.2$. For $z > 0.2$ the restrictive kinematics of the D^{*+} decay give it a signal-to-background advantage over the D^0 decay of two orders of magnitude. For $0.2 < z < 0.4$, there is no obvious D^{*+} signal above the background. However, for $z > 0.4$, where the background is at a very low level, a clear D^{*+} peak may be seen. The observed width of the D^{*+} ($\sigma = 1$ MeV/c^2) is consistent with that expected from experimental resolution alone. The D^{*+}-D^0 mass difference was determined by a maximum-likelihood fit to be 145.5 ± 0.5 MeV/c^2, where the error

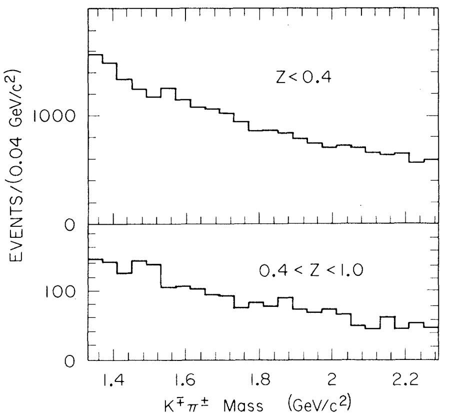

FIG. 1. The $K^-\pi^+ + K^+\pi^-$ mass spectrum for two bands of $z = 2E_D/E_{\text{c.m.}}$.

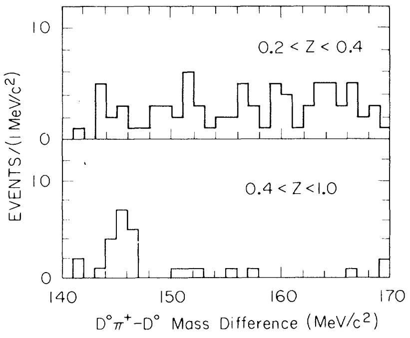

FIG. 2. The $D^0\pi^+$-D^0 mass difference for two bands of $z = 2E_{D^*}/E_{\text{c.m.}}$. For $0.2 < z < 0.4$, there is no clear signal above the background. For $z > 0.4$, a clear D^{*+} signal may be seen above a very low background level.

is dominated by the systematic error. This value is in good agreement with the previously reported values[5] averaging 145.5 ± 0.3 MeV/c^2.

In order to get an inclusive energy spectrum the D^{*+} events were defined to be those with a mass difference of 144–147 MeV/c^2, and a background subtraction and efficiency correction were performed for each bin of 0.2 in z. The background contribution to the D^{*+}'s was estimated by extrapolation of the data in the mass-difference plot (Fig. 2) outside the D^{*+} mass peak, and by use of two bands in the $K\pi$ mass plot outside the D^0 mass region. A total of 16 events were found with $z > 0.4$, where 1.0 would be expected from background processes. For $0.2 < z < 0.4$ the observed events are consistent with all being due to background processes. The efficiency for D^{*+} detection was estimated by means of a Monte Carlo program that produced D^{*+}'s as the fragmentation product of charmed quarks in a standard QCD model which included initial-state bremsstrahlung. The efficiency was found to be roughly constant at a value of 24% for $z > 0.2$. The D^{*+}'s detected correspond to an inclusive cross section for D^{*+} and D^{*-} production of 0.32 ± 0.16 nb, where the error comprises the statistical error, the uncertainty in the efficiency calculation, and the errors in the measured branching fractions[3,4] (0.44 ± 0.10 for $D^{*+} \to D^0\pi^+$ and 0.030 ± 0.006 for $D^0 \to K^-\pi^+$). This cross section is surprisingly large, but has a very large uncertainty. In the standard model, one charmed particle is present in the final state for each c and b quark produced. The cross section for all individual charmed particles is then $2(\frac{4}{3} + \frac{1}{3})(1 + \alpha_s/\pi)\sigma_{\mu\mu}$, where α_s is the strong-coupling constant, and $\sigma_{\mu\mu}$ is the cross section for μ pair production (0.10 nb at 29 GeV), giving a total of 0.36 nb. The corrected $s\,d\sigma/dz$ spectrum for D^{*+} production is shown in Fig. 3. Any bin-to-bin systematic errors introduced by the background subtraction and efficiency correction are small compared with the statistical errors of the measurement.

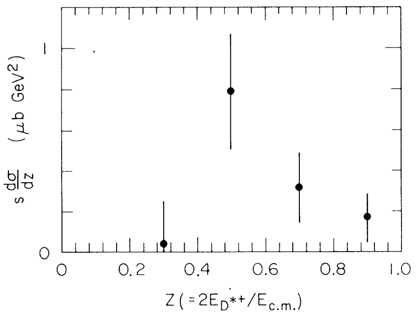

FIG. 3. The $s\,d\sigma/dz$ spectrum of produced D^{*+}'s. The errors shown are statistical only. There is an overall normalization uncertainty of ± 42%, due to uncertainties in the efficiency calculation and branching fractions used.

The average z value of the produced D^{*+}'s in the range $0.2 < z < 1.0$ is found to be 0.58 ± 0.06, calculated after background subtraction. In the standard model, up to 20% of the D^{*+} mesons may be the decay products of B mesons, but the trend of the data in Fig. 3 should closely reflect the fragmentation function of charmed quarks into mesons. Previous measurements at lower $E_{\text{c.m.}}$ have shown a D meson production spectrum that is continually falling for z values above the kinematic limit. At SPEAR, measurements were made for D^+ and D^0 mesons of $z > 0.60$,[2] and $z > 0.75$.[3] However, the data presented here for D^{*+} mesons over the wide kinematic range of $0.2 < z < 1.0$ favor a production spectrum which is peaked at an intermediate value of z. This shape is in qualitative agreement with that predicted from heavy-particle kinematic considerations.[6]

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(a)Present address: Universität Siegen, D-5900 Siegen 21, Federal Republic of Germany.

(b)Present address: Laboratoire de Physique Nucléaire et Hautes Energies, Ecole Polytechnique, F-91128 Palaiseau, France.

(c)Present address: University of Lund, S-223 62 Lund, Sweden.

(d)Present address: CERN, CH-1211 Geneva 23, Switzerland.

(e)Present address: Universität Bonn, D-53 Bonn, Federal Republic of Germany.

(f)Present address: Centre d'Etudes Nucleaires Saclay, F-91190 Gif-sur-Yvette, France.

(g)Present address: Institute of High Energy Physics, Academia Sinica, Beijing, People's Republic of China.

(h)Present address: Université de Genève, CH-1211 Geneva 4, Switzerland.

[1] Indirect evaluations have been reported from neutrino-nucleon scattering. A. Benvenuti *et al.*, Phys. Rev. Lett. <u>18</u>, 1204 (1978); N. Armenise *et al.*, Phys. Lett. <u>86B</u>, 115 (1979); J. Knobloch, in *Proceedings of*

the International Conference on Neutrino Physics and Astrophysics: Neutrino 81, Maui, Hawaii, 1981, edited by R. J. Cence, E. Ma, and A. Roberts (Univ. of Hawaii Press, Honolulu, 1982).

[2] P. A. Rapidis *et al.*, Phys. Lett. 84B, 507 (1979).

[3] M. W. Coles *et al.*, Stanford Linear Accelerator Center–Lawrence Berkeley Laboratory Report No. SLAC PUB-2916, LBL 14402, 1982 (to be published).

[4] R. H. Schindler *et al.*, Phys. Rev. D 24, 78 (1981).

[5] G. J. Feldman *et al.*, Phys. Rev. Lett. 38, 1313 (1977); J. Blietschau *et al.*, Phys. Lett. 86B, 108 (1979); V. L. Fitch *et al.*, Phys. Rev. Lett. 46, 761 (1981).

[6] C. Peterson *et al.*, Stanford Linear Accelerator Center Report No. SLAC PUB-2912, 1982 (unpublished). They suggest a form $d\sigma/dz = (A/z)[1-z^{-1}-\epsilon/(1-z)]^{-2}$, where A is the normalization, and ϵ a parameter related to the quark masses.