D_s^+ Decays to $\eta\pi^+$ and $\eta'\pi^+$

J. Alexander,[1] C. Bebek,[1] K. Berkelman,[1] D. Besson,[1] T. E. Browder,[1] D. G. Cassel,[1] E. Cheu,[1] D. M. Coffman,[1] P. S. Drell,[1] R. Ehrlich,[1] R. S. Galik,[1] M. Garcia-Sciveres,[1] B. Geiser,[1] B. Gittelman,[1] S. W. Gray,[1] D. L. Hartill,[1] B. K. Heltsley,[1] K. Honscheid,[1] J. Kandaswamy,[1] N. Katayama,[1] P. C. Kim,[1] D. L. Kreinick,[1] J. D. Lewis,[1] G. S. Ludwig,[1] J. Masui,[1] J. Mevissen,[1] N. B. Mistry,[1] S. Nandi,[1] C. R. Ng,[1] E. Nordberg,[1] C. O'Grady,[1] J. R. Patterson,[1] D. Peterson,[1] M. Pisharody,[1] D. Riley,[1] M. Sapper,[1] M. Selen,[1] H. Worden,[1] M. Worris,[1] P. Avery,[2] A. Freyberger,[2] J. Rodriguez,[2] J. Yelton,[2] S. Henderson,[3] K. Kinoshita,[3] F. Pipkin,[3] M. Saulnier,[3] R. Wilson,[3] J. Wolinski,[3] D. Xiao,[3] H. Yamamoto,[3] A. J. Sadoff,[4] R. Ammar,[5] P. Baringer,[5] D. Coppage,[5] R. Davis,[5] M. Kelly,[5] N. Kwak,[5] H. Lam,[5] S. Ro,[5] Y. Kubota,[6] J. K. Nelson,[6] D. Perticone,[6] R. Poling,[6] S. Schrenk,[6] M. S. Alam,[7] I. J. Kim,[7] B. Nemati,[7] V. Romero,[7] C. R. Sun,[7] P.-N. Wang,[7] M. M. Zoeller,[7] G. Crawford,[8] R. Fulton,[8] K. K. Gan,[8] T. Jensen,[8] H. Kagan,[8] R. Kass,[8] R. Malchow,[8] F. Morrow,[8] J. Whitmore,[8] P. Wilson,[8] F. Butler,[9] X. Fu,[9] G. Kalbfleisch,[9] M. Lambrecht,[9] P. Skubic,[9] J. Snow,[9] P.-L. Wang,[9] D. Bortoletto,[10] D. N. Brown,[10] J. Dominick,[10] R. L. McIlwain,[10] D. H. Miller,[10] M. Modesitt,[10] E. I. Shibata,[10] S. F. Schaffner,[10] I. P. J. Shipsey,[10] M. Battle,[11] J. Ernst,[11] H. Kroha,[11] S. Roberts,[11] K. Sparks,[11] E. H. Thorndike,[11] C.-H. Wang,[11] M. Artuso,[12] M. Goldberg,[12] T. Haupt,[12] N. Horwitz,[12] R. Kennett,[12] G. C. Moneti,[12] Y. Rozen,[12] P. Rubin,[12] T. Skwarnicki,[12] S. Stone,[12] M. Thusalidas,[12] W.-M. Yao,[12] G. Zhu,[12] A. V. Barnes,[13] J. Bartelt,[13] S. E. Csorna,[13] V. Jain,[13] T. Letson,[13] M. D. Mestayer,[13] D. S. Akerib,[14] B. Barish,[14] D. F. Cowen,[14] G. Eigen,[14] R. Stroynowski,[14] J. Urheim,[14] A. J. Weinstein,[14] R. J. Morrison,[15] H. Tajima,[15] D. Schmidt,[15] M. Procario,[16] M. Daoudi,[17] W. T. Ford,[17] D. R. Johnson,[17] K. Lingel,[17] M. Lohner,[17] P. Rankin,[17] and J. G. Smith[17]

(CLEO Collaboration)

[1]*Cornell University, Ithaca, New York 14853*
[2]*University of Florida, Gainesville, Florida 32611*
[3]*Harvard University, Cambridge, Massachusetts 02138*
[4]*Ithaca College, Ithaca, New York 14850*
[5]*University of Kansas, Lawrence, Kansas 66045*
[6]*University of Minnesota, Minneapolis, Minnesota 55455*
[7]*State University of New York at Albany, Albany, New York 12222*
[8]*Ohio State University, Columbus, Ohio 43210*
[9]*University of Oklahoma, Norman, Oklahoma 73019*
[10]*Purdue University, West Lafayette, Indiana 47907*
[11]*University of Rochester, Rochester, New York 14627*
[12]*Syracuse University, Syracuse, New York 13244*
[13]*Vanderbilt University, Nashville, Tennessee 37235*
[14]*California Institute of Technology, Pasadena, California 91125*
[15]*University of California at Santa Barbara, Santa Barbara, California 93106*
[16]*Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213*
[17]*University of Colorado, Boulder, Colorado 80309-0390*
(Received 27 September 1991)

Using the CLEO II detector, we have accurately measured D_s decay branching ratios relative to the $\phi\pi^+$ mode for the $\eta\pi^+$ and $\eta'\pi^+$ states, for which there are conflicting claims; our results are $0.54 \pm 0.09 \pm 0.06$ and $1.20 \pm 0.15 \pm 0.11$, respectively.

PACS numbers: 13.25.+m, 14.40.Jz

The D_s^+ was first observed in the $\phi\pi^+$ decay mode [1]. Since then a number of other hadronic decay modes have been found and $D_s^+ \to \phi l^+ \nu$ has been seen [2]. The dominant pseudoscalar-pseudoscalar modes are expected to be $\eta\pi^+$ and $\eta'\pi^+$ due to the large $s\bar{s}$ content in the η and η'. There are inconsistent measurements and limits for the branching ratios of these modes [3-7]. Here we present new measurements of these modes. In the accompanying Letter we give results for $\eta\rho^+$, $\eta'\rho^+$, and $\phi\rho^+$.

The data were collected with the CLEO II detector at the Cornell Electron Storage Ring (CESR). We use a total of 689 pb^{-1} from the $\Upsilon(3S)$ and $\Upsilon(4S)$ resonances

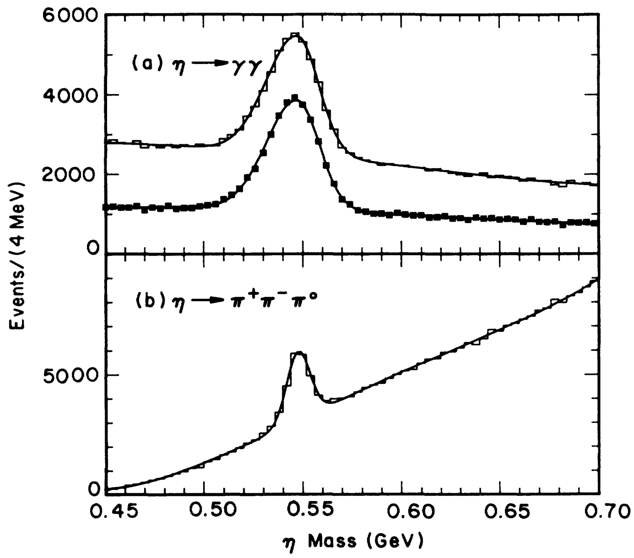

FIG. 1. (a) The $\gamma\gamma$ invariant-mass distribution for $\gamma\gamma$ momenta above 1.5 GeV/c (histogram). Removing π^0 candidates with momenta above 0.8 GeV/c produces the distribution shown with solid points. (b) The $\pi^+\pi^-\pi^0$ invariant-mass distribution for candidate momenta above 1.5 GeV/c.

and from e^+e^- center-of-mass energies just below and above the $\Upsilon(4S)$ resonance.

The CLEO II detector is designed to detect both charged and neutral particles with high resolution and efficiency. The detector includes a charged particle tracking system surrounded by a time-of-flight scintillation system and an electromagnetic shower detector consisting of 7800 thallium-doped CsI crystals. These elements are installed inside a 1.5-T superconducting coil. More detailed descriptions of the detector components can be found elsewhere [8].

In this analysis, only photon candidates in the barrel region of the detector are used, i.e., $|\cos\theta| < 0.7$, where θ is the angle with respect to the beam direction. Each neutral energy cluster is required to have at least 30 MeV of energy and not match to a charged track projected into the calorimeter. Charged tracks were required to have measured ionization losses (dE/dx) consistent within 2.5 standard deviations of that expected for the particular hypothesis under consideration. All D_s^+ candidates are required to have $x = P_{D_s}E_{\text{beam}} > 0.567$ (approximately 3 GeV/c), in order to reduce background mass combinations. To reduce background from $\Upsilon(3S)$ resonance events, we require that the ratio of Fox-Wolfram moments, H_2/H_0, be greater than 0.2 for this portion of the data sample [9]. All states considered in this work have their charge conjugate states also included in the analysis.

We select $\phi \to K^+K^-$, $\eta \to \gamma\gamma$ and $\pi^+\pi^-\pi^0$ (see Fig. 1), and $\eta' \to \eta\pi^+\pi^-$ and $\rho^0\gamma$. For $\eta \to \gamma\gamma$ and $\pi^0 \to \gamma\gamma$ decays we require that the decay angle cosine between both of the γ's and the $\gamma\gamma$ direction in the laboratory transformed into the $\gamma\gamma$ rest frame be smaller than 0.8.

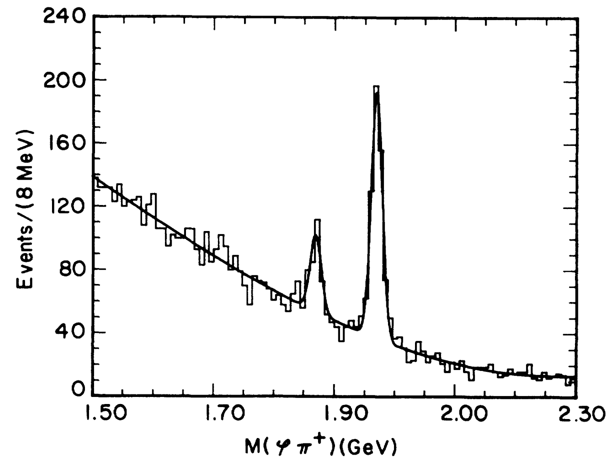

FIG. 2. The $\phi\pi^+$ invariant-mass spectrum.

Details of the selection and analysis used here are available elsewhere [10]. We note here that the rms width of the η in the $\gamma\gamma$ mode is 14 MeV.

We first describe our method of measuring the $\phi\pi^+$ decay mode. After selecting ϕ mesons within ± 8 MeV of the peak mass, we form the $\phi\pi^+$ mass spectrum shown in Fig. 2. There are two additional restrictions imposed on the data. Since the D_s has spin zero, the angular distribution of the ϕ in the D_s rest frame with respect to the D_s direction must be uniform. Background tends to peak in the forward direction (in other decay modes also in the backward direction) and we require the cosine of this "decay angle," $\cos\alpha_\phi$, to be less than 0.8. In addition, this decay involves a spin-zero particle decaying into a spin-one ϕ and a spin-zero π. Thus the ϕ must be polarized in

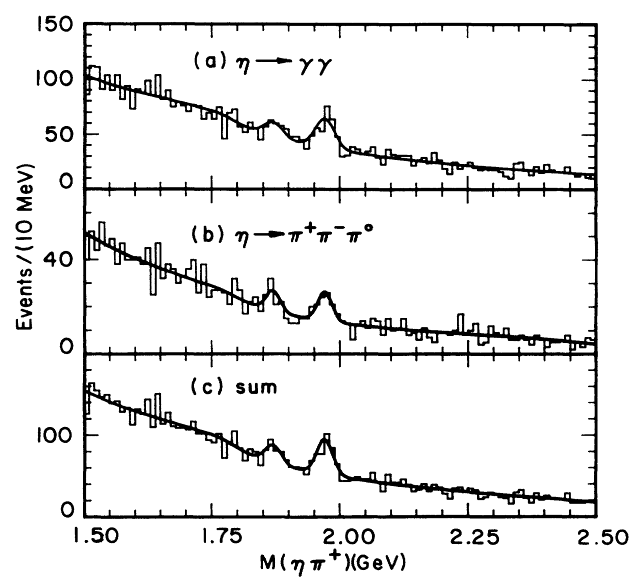

FIG. 3. The $\eta\pi^+$ invariant-mass spectrum using (a) the $\eta \to \gamma\gamma$ decay mode and (b) the $\eta \to \pi^+\pi^-\pi^0$ decay mode; (c) the sum of the two modes. The fit is described in the text.

TABLE I. Cuts used in forming D_s candidates. For η or $\pi^0 \to \gamma\gamma$, we require that the decay angle cosine between both of the γ's and the $\gamma\gamma$ direction in the laboratory transformed into the $\gamma\gamma$ rest frame be smaller than 0.8.

Mode	$s\bar{s}$ decay (ϕ,η,η')	Momentum (GeV)	Mass [a] (MeV)	Helicity angle	Decay angle
$\phi\pi^+$	K^+K^-		± 8	$\lvert\cos\theta_{K^+}\rvert > 0.45$	$\cos\alpha_\phi < 0.8$
$\eta\pi^+$	$\gamma\gamma$		$\pm$ (34–37) [b]		$\lvert\cos\alpha_\eta\rvert < 0.8$
	$\pi^+\pi^-\pi^0$	$P_{\pi^0} > 0.3$	± 15		$\lvert\cos\alpha_\eta\rvert < 0.8$
$\eta'\pi^+$	$\eta\pi^+\pi^-$	$P_\eta > 0.3$	$\pm 15, \pm 23$		$\lvert\cos\alpha_{\eta'}\rvert < 0.8$
	$\rho^0\gamma$	$P_\gamma > 0.1$	± 28	$\lvert\cos\theta_{\pi^+}\rvert < 0.8$	$\lvert\cos\alpha_{\eta'}\rvert < 0.8$ [c]

[a] Mass cut on the primary $s\bar{s}$ system. For $\eta'\pi^+$ the first number is for the $\eta \to \gamma\gamma$ mode, and the second is for the $\eta \to \pi^+\pi^-\pi^0$ mode.
[b] Cut varies as a function of $\gamma\gamma$ momentum.
[c] In addition, the γ direction in the η' rest frame is required to have $\cos\alpha_\gamma > -0.5$.

the helicity-zero state, giving a $\cos^2\phi_{K^+}$ distribution to the kaons, where θ_{K^+} is the angle between the K^+ and the D_s in the ϕ rest frame. We require $\lvert\cos\theta_{K^+}\rvert > 0.45$. There are two clear peaks in the mass distribution, one from D_s decay and the other from D^+ decay. We find 453 ± 28 D_s decays in this mode.

In Fig. 3 we show the $\eta\pi^+$ invariant-mass spectrum for both η decay modes. Selection criteria are given in Table I. In the case of the $\pi^+\pi^-\pi^0$ decay mode, we require that the π^0 momentum be greater than 0.3 GeV/c to reduce background from slow π^0's. The fit to this mass spectrum includes a peak at the D^+ mass and the reflection from the decay $D_s^+ \to \eta\rho^+$. In the latter decay mode, the ρ^+ is fully polarized and the $\eta\pi^+$ submass reflects into an approximately 150-MeV-wide region. The shape of the latter contribution is obtained from Monte Carlo studies and the size determined from the branching ratio, presented in the accompanying Letter. We also fitted the data with a Gaussian signal function of fixed mass and width, the latter determined from Monte Carlo studies, together with a third-order polynomial background. For the latter fit, a 150-MeV-wide region is excluded from the fit because of possible contamination from $D^+ \to \eta\pi^+$ decay and from $D_s^+ \to \eta\rho^+$ decay. We found that the number of decays obtained in the mode $D_s^+ \to \eta\pi^+$ is the same within 5% for both procedures.

The number of D_s events is listed in Table II. To find a branching ratio relative to the $\phi\pi^+$ mode, efficiencies for the two modes were obtained from Monte Carlo simulations; the products of the efficiency times the branching ratio, $\epsilon\mathcal{B}$, for the daughter decays are also listed in Table II. We have performed checks on the efficiencies of the Monte Carlo simulation: for example, we find $\Gamma(\eta \to \gamma\gamma)/\Gamma(\eta \to \pi^+\pi^-\pi^0) = 1.66 \pm 0.03 \pm 0.11$, which compares well with the "known" ratio [2] of 1.64 ± 0.04.

Averaging over the two η decay modes, we find $\Gamma(D_s \to \eta\pi^+)/\Gamma(D_s \to \phi\pi^+) = 0.54 \pm 0.09 \pm 0.04$. The first error is statistical and the second systematic. (Whenever two errors are quoted we follow this convention.) The systematic errors for the efficiencies relative to the $\phi\pi^+$ mode have several sources and differ slightly from mode to mode. For the $\eta\pi^+$ mode with the subsequent decay of the $\eta \to \gamma\gamma$ the systematic error includes uncertainties

TABLE II. Relative branching ratios for D_s modes.

Mode	$s\bar{s}$	Events	$\epsilon\mathcal{B}$ (%)	$\Gamma/\Gamma(\phi\pi^+)$
$\phi\pi^+$	K^+K^-	453 ± 28	17.0	1
$\eta\pi^+$	$\gamma\gamma$	123 ± 24	8.17	$0.56 \pm 0.11 \pm 0.07$
	$\pi^+\pi^-\pi^0$	42 ± 12	3.14	$0.49 \pm 0.15 \pm 0.07$
$\eta'\pi^+$	$\eta\pi^+\pi^-$ [a]	59 ± 11	2.05	$1.10 \pm 0.21 \pm 0.12$
	$\rho^0\gamma$	200 ± 34	5.40	$1.38 \pm 0.25 \pm 0.20$
	$\eta\pi^+\pi^-$ [b]	22 ± 7	0.75	$1.12 \pm 0.36 \pm 0.15$

[a] For $\eta \to \gamma\gamma$. [b] For $\eta \to \pi^+\pi^-\pi^0$.

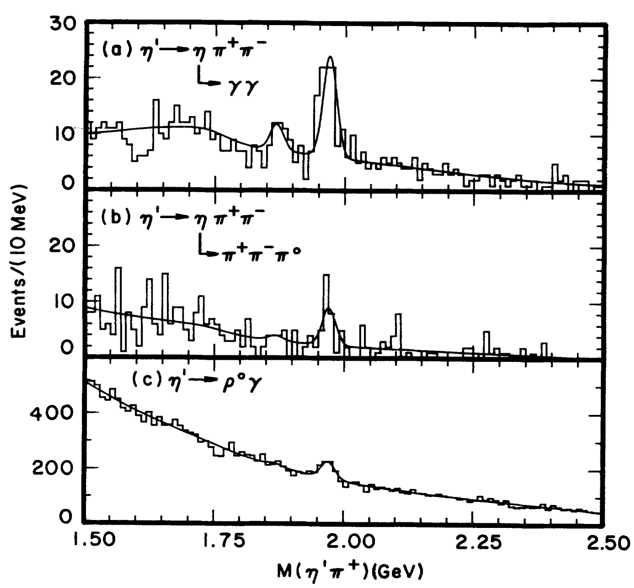

FIG. 4. The $\eta'\pi^+$ invariant-mass spectrum using the $\eta' \to \eta\pi^+\pi^-$ decay mode, for the cases (a) $\eta \to \gamma\gamma$ and (b) $\eta \to \pi^+\pi^-\pi^0$, and for the (c) $\eta' \to \rho^0\gamma$ decay mode. The fits are described in the text.

TABLE III. Recent measurements of $\eta\pi^+$ and $\eta'\pi^+$.

Experiment	$\Gamma(\eta\pi^+)/\Gamma(\phi\pi^+)$	$\Gamma(\eta'\pi^+)/\Gamma(\phi\pi^+)$
CLEO II	$0.54\pm0.09\pm0.06$	$1.20\pm0.15\pm0.11$
E691 [3]	<1.5 at 90% C.L.	<1.3 at 90% C.L.
Mark II [4]	4.0 ± 1.3	6.4 ± 2.8
Mark III [5]	<2.5 at 90% C.L.	<1.9 at 90% C.L.
NA14/2 [6]		$2.5\pm1.0^{+1.5}_{-0.4}$
ARGUS [7]		2.5 ± 0.7

from fitting the $\eta\pi^+$ mass spectrum (6%) which contains both the effect of the $\eta\rho^+$ reflection and different assumed background shapes, uncertainties in the relative charged track (4%) and photon detection efficiencies (5%), statistics from the Monte Carlo simulation (4%), uncertainties in the relative hadronic event selection efficiencies (5%), and uncertainties in the π^0 veto efficiency (3%). The total systematic error is obtained by adding these uncorrelated errors in quadrature and is estimated to be $\pm12\%$.

In Fig. 4 we show the $\eta'\pi^+$ invariant-mass spectrum for all three η' decay modes studied, namely, $\eta'\to\eta\pi^+\pi^-$, with (a) $\eta\to\gamma\gamma$ and (b) $\eta\to\pi^+\pi^-\pi^0$, and (c) $\eta'\to\rho\gamma$. Again, the shape of the mass spectrum below the D_s mass was studied carefully in the same manner as for the $\eta\pi^+$ decay mode above. The fits allow for a peak at the D^+ mass and takes account of the reflection from the $\eta'\rho^+$ decay mode. Both the shape and the amount of this reflection are obtained in the same way as for the fit described above for the $\eta\rho^+$ decay mode. Event yields and efficiencies are given in Table II. The average branching ratio for the three η' final states is $1.20\pm0.15\pm0.18$ times the branching ratio for the decay $\phi\pi^+$.

Our results for these two modes are compared with others in Table III. Our measurements are much smaller than previous claims, for both modes.

We compare our results with the models of Bauer, Stech, and Wirbel (BSW) [11], and Kamal, Sinha, and Sinha (KSS) [12] who have modified the BSW results by changing the value of the η-η' mixing angle Θ from $-11°$ to the value found by Gilman and Kauffman [13], namely, $\Theta=-19°$ (BSW′). BSW used the value of $\Theta=-11°$. KSS also give their own predictions. We also include predictions from QCD sum rules, as determined by Blok and Shifman (BS) [14]. None of the models agree with the data. In Table IV we compare our results with these models.

In summary, we have measured the branching ratios, relative to the $\phi\pi^+$ mode, of the $\eta\pi^+$ and $\eta'\pi^+$ modes to be $0.54\pm0.09\pm0.06$ and $1.20\pm0.15\pm0.11$, respectively, much smaller than previous claims. Current theoretical models do not give a good description of these results.

TABLE IV. $\Gamma/\Gamma(\phi\pi^+)$ compared with theory.

Mode	This experiment	BSW	BSW′	KSS	BS
$\eta\pi^+$	$0.54\pm0.09\pm0.06$	1.04	0.75	1.35	1.13
$\eta'\pi^+$	$1.20\pm0.15\pm0.11$	0.61	0.78	1.47	0.10

We gratefully acknowledge the effort of the CESR staff in providing us with excellent luminosity and running conditions. We thank BDH Ltd. (now called Merck Ltd.), Poole, England, and Horiba Ltd., Kyoto, Japan, for their superb efforts in manufacturing high-quality crystals for the CLEO II detector. P.S.D. thanks the PYI program of the NSF, K.H. thanks the Alexander von Humboldt Stiftung Foundation, G.E. thanks the Heisenberg Foundation, and R.P. and P.R. thank the A. P. Sloan Foundation for support. This work was supported by the National Science Foundation and the U.S. Department of Energy.

[1] CLEO Collaboration, A. Chen *et al.*, Phys. Rev. Lett. **51**, 634 (1983).

[2] Particle Data Group, J. J. Hernández *et al.*, Phys. Lett. B **239**, 1 (1990).

[3] For $\eta\pi^+$, E691 Collaboration, J. C. Anjos *et al.*, Phys. Lett. B **223**, 267 (1989); for $\eta'\pi^+$, Phys. Rev. D **43**, R2063 (1991).

[4] Mark II Collaboration, G. Wormser *et al.*, Phys. Rev. Lett. **61**, 1057 (1988).

[5] Mark III Collaboration, P. Kim, in *Heavy Quark Physics*, edited by P. Drell and D. Rubin (American Institute of Physics, New York, 1989).

[6] NA14/2 Collaboration, M. P. Alvarez *et al.*, Phys. Lett. B **255**, 639 (1991).

[7] ARGUS Collaboration, H. Albrecht *et al.*, Phys. Lett. B **245**, 315 (1990).

[8] Y. Kubota *et al.*, Cornell University Report No. CLNS 91-1122, 1991 (unpublished); E. Blucher *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **249**, 201 (1986); C. Bebek *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **265**, 258 (1988); the crystal calibration is described by R. Morrison *et al.*, Phys. Rev. Lett. **67**, 1696 (1991).

[9] G. Fox and S. Wolfram, Phys. Rev. Lett. **41**, 1581 (1978).

[10] M. Daoudi *et al.*, Cornell University Report No. CLNS 91/1108, 1991 (to be published).

[11] M. Bauer, B. Stech, and M. Wirbel, Z. Phys. C **34**, 103 (1987).

[12] A. N. Kamal, N. Sinha, and R. Sinha, Phys. Rev. D **38**, 1612 (1988).

[13] F. J. Gilman and R. Kauffmann, Phys. Rev. D **36**, 2761 (1987).

[14] B. Yu. Blok and M. A. Shifman, Yad. Fiz. **45**, 841 (1987) [Sov. J. Nucl. Phys. **45**, 522 (1987)].