Observation of $D_s^+ K^-$ and Evidence for $D_s^+ \pi^-$ Final States in Neutral B Decays

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 0031-9007/02/89(23)/231804(6)$20.00

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(Received 6 August 2002; published 18 November 2002)

We report the first observation of a B meson decay that is not accessible by a direct spectator process. The channel $\bar{B}^0 \to D_s^+ K^-$ is found in a sample of 85×10^6 $B\bar{B}$ events, collected with the Belle detector at KEKB, with a branching fraction $\mathcal{B}(\bar{B}^0 \to D_s^+ K^-) = (4.6^{+1.2}_{-1.1} \pm 1.3) \times 10^{-5}$. We also obtain evidence for the $B^0 \to D_s^+ \pi^-$ decay with branching fraction $\mathcal{B}(B^0 \to D_s^+ \pi^-) = (2.4^{+1.0}_{-0.8} \pm 0.7) \times 10^{-5}$. This value may be used to extract a model-dependent value of $|V_{ub}|$.

DOI: 10.1103/PhysRevLett.89.231804 PACS numbers: 13.25.Hw, 14.40.Nd

Although the B mesons decay primarily through the spectator processes, other processes such as W exchange and final state interactions (FSI) may contribute appreciably, especially [1] for rare modes that are now emerging at the B factory experiments. As the focus of CP asymmetry studies shifts to rarer modes, it is important to quantify the effects due to nonspectator and FSI processes, as they are often necessary for generating measurable CP asymmetries. Since the nonspectator effects carry significant theoretical uncertainties, a quantitative understanding must be developed before we can extract Cabibbo-Kobayashi-Maskawa matrix parameters.

Important insight in this regard can be gained by experimental measurement of channels where nonspectator processes dominate. We report here the first observation of a mode that is not directly accessible through the spectator process. The mode $\bar{B}^0 \to D_s^+ K^-$ may occur via W exchange or final state rescattering, and predictions for its branching fraction vary over a wide range, 3×10^{-6}–10^{-4} [1–4]. The search for $\bar{B}^0 \to D_s^+ K^-$ also encompasses $B^0 \to D_s^+ \pi^-$, a mode that is expected to be dominated by a (spectator) $b \to u$ transition. As it lacks a penguin contribution, it can in principle provide a way to determine $|V_{ub}|$ [5].

The results reported here are based on a 78.7 fb^{-1} data sample, collected with the Belle detector [6] at the KEKB asymmetric energy e^+e^- collider [7] at the center-of-mass (c.m.) energy of the $\Upsilon(4S)$ resonance and containing 85.0×10^6 produced $B\bar{B}$ pairs. A 7.5 fb^{-1} data sample taken at a c.m. energy that is 60 MeV below the $\Upsilon(4S)$ resonance is used for systematic studies of the $e^+e^- \to q\bar{q}$ background.

The Belle detector has been described elsewhere [6]. Charged tracks are selected with requirements based on the average hit residual and impact parameter relative to the interaction point (IP). We also require that the transverse momentum of the tracks be greater than 0.1 GeV/c in order to reduce the low momentum combinatorial background. For charged particle identification (PID) the combined information from specific ionization in the central drift chamber (dE/dx), time-of-flight scintillation counters, and aerogel Čerenkov counters (ACC) is used. At large momenta (>2.5 GeV$/c$) only the ACC and dE/dx are used. Charged kaons are selected with PID criteria that have an efficiency of 88%, a pion misidentification probability of 8%, and negligible contamination from protons. The criteria for charged pions have an efficiency of 89% and a kaon misidentification probability of 9%. All tracks that are positively identified as electrons are rejected.

Neutral kaons are reconstructed via the decay $K_S^0 \to \pi^+\pi^-$. The two-pion invariant mass is required to be within 6 MeV$/c^2$ ($\sim 2.5\sigma$) of the nominal K^0 mass, and the displacement of the $\pi^+\pi^-$ vertex from the IP in the transverse r-ϕ plane is required to be between 0.1 and 20 cm. The directions in the r-ϕ projection of the K_S^0 candidate's flight path and momentum are required to agree within 0.2 rad.

We reconstruct D_s^+ mesons in the channels $D_s^+ \to \phi\pi^+$, $\bar{K}^{*0}K^+$, and $K_S^0K^+$ (inclusion of charge conjugate states is implicit throughout this Letter). ϕ (K^{*0}) mesons are formed from the K^+K^- ($K^+\pi^-$) pairs with invariant mass within 10 MeV$/c^2$ (50 MeV$/c^2$) of the nominal ϕ (K^{*0}) mass. We select D_s^+ mesons in a wide (± 0.5 GeV$/c^2$) window, for subsequent studies; the $M(D_s)$ signal region is defined to be within 12 MeV$/c^2$ ($\sim 2.5\sigma$) of the nominal D_s^+ mass. D_s^+ candidates are combined with a charged kaon or pion to form a B meson. Candidate events are identified by their c.m. energy difference, $\Delta E = (\sum_i E_i) - E_b$, and the beam constrained mass, $M_{\rm bc} = \sqrt{E_b^2 - (\sum_i \vec{p}_i)^2}$, where $E_b = \sqrt{s}/2$ is the beam energy and $\vec{p}_i$ and E_i are the momenta and energies of the decay products of the B meson in the c.m. frame. We select events with $M_{\rm bc} > 5.2$ GeV$/c^2$ and $|\Delta E| < 0.2$ GeV and define the B signal region to be 5.272 GeV$/c^2 < M_{\rm bc} < 5.288$ GeV$/c^2$ and $|\Delta E| < 0.03$ GeV. The $M_{\rm bc}$ sideband is defined as 5.20 GeV$/c^2 < M_{\rm bc} < 5.26$ GeV$/c^2$. We use a Monte Carlo (MC) simulation to determine the efficiency [8].

To suppress the large combinatorial background that is dominated by the two-jet-like $e^+e^- \to q\bar{q}$ continuum process, variables that characterize the event topology are used. We require $|\cos\theta_{\rm thr}| < 0.80$, where $\theta_{\rm thr}$ is the angle between the thrust axis of the B candidate and that of the rest of the event. This requirement eliminates 77% of the continuum background and retains 78% of the signal events. We also define a Fisher discriminant, $\mathcal{F}$, that includes the production angle of the B candidate, the angle of the B candidate thrust axis with respect to the beam axis, and nine parameters that characterize the momentum flow in the event relative to the B candidate thrust axis in the c.m. frame [9]. We impose a requirement on $\mathcal{F}$ that rejects 50% of the remaining continuum background and retains 92% of the signal.

We also consider possible backgrounds from $q\bar{q}$ events containing real D_s^+ mesons. These events peak in the $M(D_s)$ spectra but not in the ΔE and $M_{\rm bc}$ distributions. We study this background using the $M_{\rm bc}$ sideband and find it to be fewer than 0.1 and 0.5 events for the $\bar{B}^0 \to D_s^+K^-$ and $B^0 \to D_s^+\pi^-$ modes, respectively.

Other B decays, such as $\bar{B}^0 \to D^+\pi^-$, $D^+ \to K^-\pi^+\pi^+$, with one pion misidentified as a kaon, require particular attention because they have large branching fractions and can peak in the $M_{\rm bc}$ signal region. The reconstructed invariant mass spectra for these events overlap with the signal D_s^+ mass region, while their ΔE distribution is shifted by about 50 MeV$/c^2$. To suppress this background, we exclude event candidates that are consistent with the $D^+ \to K^-\pi^+\pi^+$ mass hypothesis within 15 MeV$/c^2$ ($\sim 3\sigma$) when the two same-sign particles are considered to be pions, independently of their PID information. For the $D_s^+ \to K_S^0K^+$ mode there is a similar background from $\bar{B}^0 \to D^+\pi^-$, $D^+ \to K_S^0\pi^+$. In this case we exclude candidates consistent within 20 MeV$/c^2$ ($\sim 3\sigma$) with the $D^+ \to K_S^0\pi^+$ hypothesis.

Possible backgrounds from B decays via $b \to c$ transitions ($B \to D_sDX$) are also considered. The D_s^+ from these decays have a lower momentum and are kinematically separated from the signal. We analyzed a MC sample of generic $B\bar{B}$ events corresponding to about twice the data sample and found no peaking backgrounds.

Another potential $B\bar{B}$ background is charmless $\bar{B}^0 \to K^-K^+K^-\pi^+(K_S^0K^+K^-)$. Such events peak in the ΔE and $M_{\rm bc}$ spectra, but not in the $M(D_s)$ distributions. They tend to be dominated by quasi-two-body decay channels such as $\phi\bar{K}^{(*)0}$ [10,11]. To reduce this background, we reject events with low (<2 GeV$/c^2$) two particle invariant masses: $M_{K^-\pi^+}$ and $M_{\phi K^-}$ for the $D_s^+ \to \phi\pi^+$ channel, $M_{K^+K^-}$ and $M_{\bar{K}^{*0}K^-}$ for $D_s^+ \to \bar{K}^{*0}K^+$, and $M_{K^+K^-}$ and $M_{K_S^0K^-}$ for $D_s^+ \to K_S^0K^+$. The remaining background from these sources, if any, is excluded by fitting the $M(D_s)$ distribution.

The scatter plots in ΔE and $M_{\rm bc}$ for the $\bar{B}^0 \to D_s^+K^-$ and $B^0 \to D_s^+\pi^-$ candidates in the $M(D_s)$ signal region are shown in Fig. 1; a significant enhancement in the B signal region is observed. Figure 2 shows the $M(D_s)$ spectra for selected $\bar{B}^0 \to D_s^+K^-$ and $B^0 \to D_s^+\pi^-$ candidates in the B signal region. In addition to clear signals at the D_s^+ mass in Fig. 2, we observe peaks at the D^+ mass, corresponding to $\bar{B}^0 \to D^+\pi^-$ and $\bar{B}^0 \to D^+K^-$, $D^+ \to \phi\pi^+$, $\bar{K}^{*0}K^+$, $K_S^0K^+$.

Our studies have shown that the backgrounds may peak in the signal region of $M(D_s)$ or of ΔE (and $M_{\rm bc}$) but not in both simultaneously. To extract our signal, we therefore perform a binned maximum likelihood fit to the two-dimensional distribution of data in $M(D_s)$ and ΔE, separating the backgrounds from the signal component, which peaks in both. For each of the three D_s^+ decay channels the ΔE range, -0.1 GeV $< \Delta E < 0.2$ GeV, is divided into 30 bins and the $M(D_s)$ range, $1.5 < M(D_s) < 2.5$ GeV$/c^2$, into 200 bins. All bins in all D_s^+ submodes are fitted simultaneously to a sum of signal and

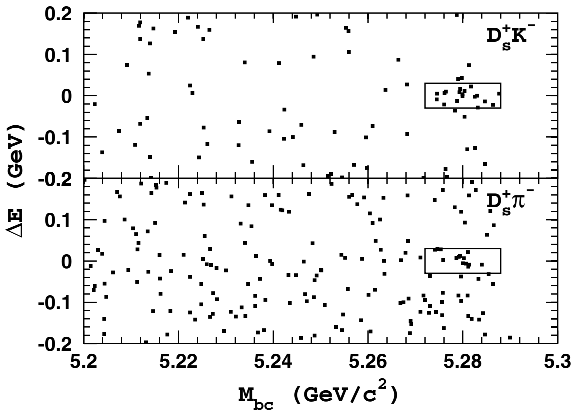

FIG. 1. The ΔE versus M_{bc} scatter plot for the $\bar{B}^0 \to D_s^+ K^-$ (top) and $B^0 \to D_s^+ \pi^-$ (bottom) candidates in the $M(D_s)$ signal region. The points represent the experimental data and the boxes show the B meson signal region.

background shapes. The D_s^+ signal is described by a two-dimensional Gaussian, with widths in both dimensions obtained and fixed using reconstructed signals in the data from $\bar{B}^0 \to D^+\pi^-(D^+ \to K^-\pi^+\pi^+, K_S\pi^+)$. The signal amplitude is constrained to correspond to the same branching fraction $\mathcal{B}(\bar{B}^0 \to D_s^+ h^-)$ for all three D_s^+ submodes. The fit also includes an additional two-dimensional Gaussian for $\bar{B}^0 \to D^+ h^-$ decays.

The background includes three components: combinatorial [flat in $M(D_s)$ and ΔE], $q\bar{q}$ events that peak in $M(D_s)$ and are flat in ΔE, and B decays that peak in ΔE and are flat in $M(D_s)$. The levels of the three components are allowed to vary independently in the three reconstructed D_s^+ modes. The fit results are given in Table I. The statistical significance quoted in Table I is defined as $\sqrt{-2\ln(\mathcal{L}_0/\mathcal{L}_{\max})}$, where $\mathcal{L}_{\max}$ and $\mathcal{L}_0$ denote the maximum likelihood with the fitted signal yield and with the signal yield fixed to zero, respectively. The results of one-dimensional fits to the $M(D_s)$ and ΔE distributions are also shown in Table I for comparison. Figures 2 and 3 show the $M(D_s)$ and ΔE projections for events from the signal region and the fitted signal plus background combined shape by solid lines and background shape including the peaking background by dashed lines. The peaking background is found to be 1.0 ± 0.5 and 1.6 ± 1.0 events for $\bar{B}^0 \to D_s^+ K^-$ and $B^0 \to D_s^+ \pi^-$, respectively.

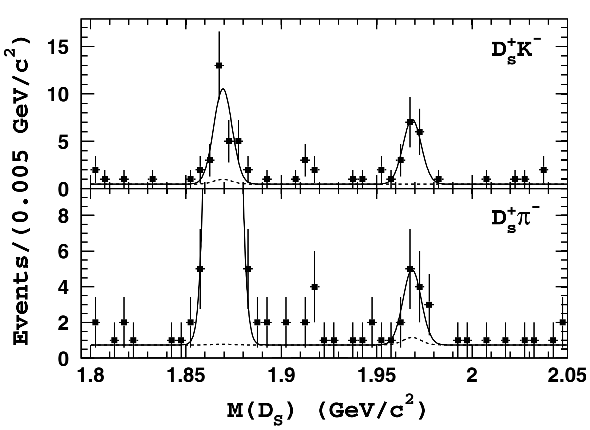

FIG. 2. The $M(D_s)$ spectra for $\bar{B}^0 \to D_s^+ K^-$ (top) and $B^0 \to D_s^+ \pi^-$ (bottom) in the B signal region. The points with errors represent experimental data and the curves display the results of the simultaneous fit described in the text.

$\bar{B}^0 \to D_s^{*+} h^-$ final states, where the low energy photon from the $D_s^* \to D_s\gamma$ decay is missed, can populate the $\bar{B}^0 \to D_s^+ h^-$ signal region. These would produce a long tail on the negative side of the ΔE distribution. In theoretical models based on factorization, the $B^0 \to D_s^{*+}\pi^-$ and $B^0 \to D_s^+\pi^-$ decay widths are predicted to be approximately equal; there are, however, no corresponding predictions for $\bar{B}^0 \to D_s^{(*)+} K^-$ decays. To study the sensitivity of the measured branching fraction to a possible $\bar{B}^0 \to D_s^{*+} h^-$ contribution, we perform a fit with an additional $\bar{B}^0 \to D_s^{*+} h^-$ component included, where the signal shape is fixed from the MC and the branching fraction is left as a free parameter. The resulting 2% difference in the $B^0 \to D_s^+\pi^-$ event yield (compared to the results presented in Table I) is added to the systematic uncertainty; the change in the $\bar{B}^0 \to D_s^+ K^-$ yield is less than 1%. We also check for cross feed between $\bar{B}^0 \to D_s^+ K^-$ and $B^0 \to D_s^+\pi^-$ due to kaon/pion misidentification. To study this we include the cross feed contributions in the simultaneous fit, with shapes fixed from the MC and misidentification probabilities obtained from data; the uncertainty due to this effect is found to be negligible ($\lesssim 1\%$).

As a check, we apply the same procedure to $\bar{B}^0 \to D^+\pi^-$ and $\bar{B}^0 \to D^+K^-$, $D^+ \to \phi\pi^+, \bar{K}^{*0}K^+, K_S^0K^+$, and obtain $\mathcal{B}(\bar{B}^0 \to D^+\pi^-) = (2.8 \pm 0.2) \times 10^{-3}$ and $\mathcal{B}(\bar{B}^0 \to D^+K^-) = (3.0 \pm 0.7) \times 10^{-4}$, which agree well with the world average values $\mathcal{B}(\bar{B}^0 \to D^+\pi^-) = (3.0 \pm 0.4) \times 10^{-3}$ and $\mathcal{B}(\bar{B}^0 \to D^+K^-) = (2.0 \pm 0.6) \times 10^{-4}$ [12].

The following sources of systematic error are found to be the most significant: tracking efficiency (2% per track), charged hadron identification efficiency (2% per particle), K_S^0 reconstruction efficiency (6%), signal-shape parametrization (5%), and MC statistics (3%). The tracking efficiency error is estimated using η decays to $\gamma\gamma$ and $\pi^+\pi^-\pi^0$. The K/π identification uncertainty is determined from $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$ decays. We assume equal production of B^+B^- and $B^0\bar{B}^0$ pairs but do not include an additional error from this assumption. The uncertainty in the D_s^+ meson branching fractions, which is dominated by the 25% error on $\mathcal{B}(D_s^+ \to \phi\pi^+)$, is also taken into account. The overall systematic uncertainty is 28%.

In summary, we report the first observation of $\bar{B}^0 \to D_s^+ K^-$ with a 6.4σ statistical significance. We find $\mathcal{B}(\bar{B}^0 \to D_s^+ K^-) = (4.6^{+1.2}_{-1.1} \pm 1.3) \times 10^{-5}$, which is

TABLE I. Results on the signal yields and branching fractions. The efficiencies do not include intermediate branching fractions.

Mode	$M(D_s)$-ΔE yield	$M(D_s)$ yield	ΔE yield	Efficiency, %	$\mathcal{B}$ (10^{-5})	Stat. significance
$\bar{B}^0 \to D_s^+ K^-$, $D_s^+ \to \phi\pi^+$	$8.9^{+3.3}_{-2.7}$	$8.9^{+3.4}_{-2.7}$	$9.0^{+3.3}_{-2.7}$	11.6 ± 0.4	$5.1^{+2.0}_{-1.6} \pm 1.4$	5.1σ
$\bar{B}^0 \to D_s^+ K^-$, $D_s^+ \to \bar{K}^{*0} K^+$	$6.1^{+3.0}_{-2.3}$	$5.1^{+2.8}_{-2.2}$	$5.9^{+3.0}_{-2.4}$	6.8 ± 0.3	$4.8^{+2.4}_{-1.8} \pm 1.3$	3.8σ
$\bar{B}^0 \to D_s^+ K^-$, $D_s^+ \to K_S^0 K^+$	$1.6^{+2.0}_{-1.2}$	$1.0^{+1.9}_{-1.0}$	$2.8^{+2.3}_{-1.6}$	7.0 ± 0.3	$2.2^{+2.8}_{-1.7} \pm 0.6$	1.6σ
$\bar{B}^0 \to D_s^+ K^-$, simultaneous fit	$16.4^{+4.6}_{-3.9}$	$15.0^{+4.5}_{-3.8}$	$17.5^{+4.8}_{-4.2}$	$\cdots$	$4.6^{+1.2}_{-1.1} \pm 1.3$	6.4σ
$B^0 \to D_s^+ \pi^-$, $D_s^+ \to \phi\pi^+$	$4.7^{+2.6}_{-2.0}$	$4.8^{+2.6}_{-1.9}$	$4.0^{+2.6}_{-2.0}$	12.9 ± 0.4	$2.4^{+1.3}_{-1.0} \pm 0.7$	3.2σ
$B^0 \to D_s^+ \pi^-$, $D_s^+ \to \bar{K}^{*0} K^+$	$3.4^{+3.2}_{-2.4}$	$2.9^{+2.8}_{-2.0}$	$4.4^{+3.3}_{-2.6}$	7.5 ± 0.3	$2.4^{+2.3}_{-1.7} \pm 0.7$	1.6σ
$B^0 \to D_s^+ \pi^-$, $D_s^+ \to K_S^0 K^+$	$1.6^{+2.3}_{-1.6}$	$2.2^{+2.2}_{-1.5}$	$0.9^{+2.2}_{-0.9}$	7.2 ± 0.3	$2.2^{+3.1}_{-2.2} \pm 0.6$	0.9σ
$B^0 \to D_s^+ \pi^-$, simultaneous fit	$10.1^{+4.4}_{-3.7}$	$10.3^{+4.1}_{-3.4}$	$9.5^{+4.5}_{-3.8}$	$\cdots$	$2.4^{+1.0}_{-0.8} \pm 0.7$	3.6σ

consistent with a calculation of the W-exchange rate in the "perturbative quantum chromodynamic factorization" approach [3], but much higher than an earlier result [2]. On the other hand, it should be noted that the recent observation of higher-than-predicted rates for $\bar{B}^0 \to D^0 h^0$ ($h^0 = \pi^0, \eta, \omega$) [13–15] and $\bar{B}^0 \to D^0\rho^0$ [16] suggest that FSI may contribute appreciably to $\bar{B}^0 \to D_s^+ K^-$ [1,4]. We also obtain evidence for $B^0 \to D_s^+\pi^-$ with $\mathcal{B}(B^0 \to D_s^+\pi^-) = (2.4^{+1.0}_{-0.8} \pm 0.7) \times 10^{-5}$ (3.6σ statistical significance). Our results are consistent with recent evidence from BaBar [17].

Since the dominant systematic uncertainty on both measurements is due to the branching fraction of $D_s^+ \to \phi\pi^+$, $\mathcal{B}_{\phi\pi}$, we also report $\mathcal{B}(\bar{B}^0 \to D_s^+ K^-) \times \mathcal{B}_{\phi\pi} = (16.4^{+4.5}_{-3.8} \pm 2.1) \times 10^{-7}$ and $\mathcal{B}(B^0 \to D_s^+\pi^-) \times \mathcal{B}_{\phi\pi} = (8.6^{+3.7}_{-3.0} \pm 1.1) \times 10^{-7}$. Using $\mathcal{B}(B^0 \to D_s^+\pi^-)/\mathcal{B}(B^0 \to D_s^+ D^-) = (0.424 \pm 0.041) \times |V_{ub}/V_{cb}|^2$ [5], and $\mathcal{B}(B^0 \to D_s^+ D^-) \times \mathcal{B}_{\phi\pi} = (3.0 \pm 1.1) \times 10^{-4}$ calculated from a CLEO result [18], we can extract a model-dependent value $|V_{ub}/V_{cb}| = (8.2^{+3.5}_{-2.9} \pm 3.4) \times 10^{-2}$, where no error on the factorization assumption or other sources of model dependence are included. This value is in agreement with ones obtained from inclusive semileptonic decays [12].

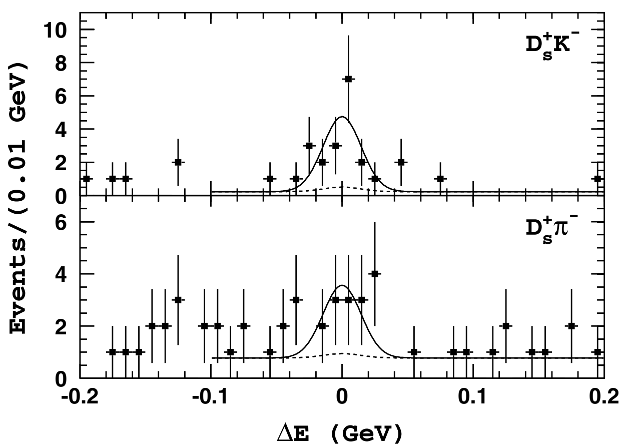

FIG. 3. The ΔE spectra for $\bar{B}^0 \to D_s^+ K^-$ (top) and $B^0 \to D_s^+\pi^-$ (bottom) in the B signal region. The points with errors are experimental data and the curves are the results of the simultaneous fit described in the text.

We thank the KEKB accelerator group for the excellent operation of the KEKB accelerator. We acknowledge support from the Ministry of Education, Culture, Sports, Science, and Technology of Japan and the Japan Society for the Promotion of Science; the Australian Research Council and the Australian Department of Industry, Science and Resources; the National Science Foundation of China under Contract No. 10175071; the Department of Science and Technology of India; the BK21 program of the Ministry of Education of Korea and the CHEP SRC program of the Korea Science and Engineering Foundation; the Polish State Committee for Scientific Research under Contract No. 2P03B 17017; the Ministry of Science and Technology of the Russian Federation; the Ministry of Education, Science and Sport of the Republic of Slovenia; the National Science Council and the Ministry of Education of Taiwan; and the U.S. Department of Energy.

*On leave from Nova Gorica Polytechnic, Nova Gorica.

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