CLNS 00/1679
CLEO 00-11

Search for Decays of B^0 Mesons Into Pairs of Leptons: $B^0 \to e^+e^-$, $B^0 \to \mu^+\mu^-$ and $B^0 \to e^\pm\mu^\mp$.

CLEO Collaboration

(July 19, 2000)

Abstract

We search for the decay of the B^0 meson into a pair of leptons in the suppressed channels $B^0 \to e^+e^-$, $B^0 \to \mu^+\mu^-$ and in the lepton number violating channel $B^0 \to e^\pm\mu^\mp$ in a sample of 9.7×10^6 $B\bar{B}$ pairs recorded by CLEO detector. No signal is found, and the following upper limits on the branching fractions are established: $\mathcal{B}(B^0 \to e^+e^-) < 8.3 \times 10^{-7}$, $\mathcal{B}(B^0 \to \mu^+\mu^-) < 6.1 \times 10^{-7}$, $\mathcal{B}(B^0 \to e^\pm\mu^\mp) < 15 \times 10^{-7}$ at 90% confidence level. A new lower limit on the Pati-Salam leptoquark mass $M_{LQ} > 27$ TeV is established at 90% confidence level.

T. Bergfeld,[1] B. I. Eisenstein,[1] J. Ernst,[1] G. E. Gladding,[1] G. D. Gollin,[1] R. M. Hans,[1] E. Johnson,[1] I. Karliner,[1] M. A. Marsh,[1] M. Palmer,[1] C. Plager,[1] C. Sedlack,[1] M. Selen,[1] J. J. Thaler,[1] J. Williams,[1] K. W. Edwards,[2] R. Janicek,[3] P. M. Patel,[3] A. J. Sadoff,[4] R. Ammar,[5] A. Bean,[5] D. Besson,[5] R. Davis,[5] N. Kwak,[5] X. Zhao,[5] S. Anderson,[6] V. V. Frolov,[6] Y. Kubota,[6] S. J. Lee,[6] R. Mahapatra,[6] J. J. O'Neill,[6] R. Poling,[6] T. Riehle,[6] A. Smith,[6] C. J. Stepaniak,[6] J. Urheim,[6] S. Ahmed,[7] M. S. Alam,[7] S. B. Athar,[7] L. Jian,[7] L. Ling,[7] M. Saleem,[7] S. Timm,[7] F. Wappler,[7] A. Anastassov,[8] J. E. Duboscq,[8] E. Eckhart,[8] K. K. Gan,[8] C. Gwon,[8] T. Hart,[8] K. Honscheid,[8] D. Hufnagel,[8] H. Kagan,[8] R. Kass,[8] T. K. Pedlar,[8] H. Schwarthoff,[8] J. B. Thayer,[8] E. von Toerne,[8] M. M. Zoeller,[8] S. J. Richichi,[9] H. Severini,[9] P. Skubic,[9] A. Undrus,[9] S. Chen,[10] J. Fast,[10] J. W. Hinson,[10] J. Lee,[10] D. H. Miller,[10] E. I. Shibata,[10] I. P. J. Shipsey,[10] V. Pavlunin,[10] D. Cronin-Hennessy,[11] A.L. Lyon,[11] E. H. Thorndike,[11] C. P. Jessop,[12] H. Marsiske,[12] M. L. Perl,[12] V. Savinov,[12] X. Zhou,[12] T. E. Coan,[13] V. Fadeyev,[13] Y. Maravin,[13] I. Narsky,[13] R. Stroynowski,[13] J. Ye,[13] T. Wlodek,[13] M. Artuso,[14] R. Ayad,[14] C. Boulahouache,[14] K. Bukin,[14] E. Dambasuren,[14] S. Karamov,[14] G. Majumder,[14] G. C. Moneti,[14] R. Mountain,[14] S. Schuh,[14] T. Skwarnicki,[14] S. Stone,[14] G. Viehhauser,[14] J.C. Wang,[14] A. Wolf,[14] J. Wu,[14] S. Kopp,[15] A. H. Mahmood,[16] S. E. Csorna,[17] I. Danko,[17] K. W. McLean,[17] Sz. Márka,[17] Z. Xu,[17] R. Godang,[18] K. Kinoshita,[18,*] I. C. Lai,[18] S. Schrenk,[18] G. Bonvicini,[19] D. Cinabro,[19] S. McGee,[19] L. P. Perera,[19] G. J. Zhou,[19] E. Lipeles,[20] S. P. Pappas,[20] M. Schmidtler,[20] A. Shapiro,[20] W. M. Sun,[20] A. J. Weinstein,[20] F. Würthwein,[20,†] D. E. Jaffe,[21] G. Masek,[21] H. P. Paar,[21] E. M. Potter,[21] S. Prell,[21] V. Sharma,[21] D. M. Asner,[22] A. Eppich,[22] T. S. Hill,[22] R. J. Morrison,[22] R. A. Briere,[23] G. P. Chen,[23] B. H. Behrens,[24] W. T. Ford,[24] A. Gritsan,[24] J. Roy,[24] J. G. Smith,[24] J. P. Alexander,[25] R. Baker,[25] C. Bebek,[25] B. E. Berger,[25] K. Berkelman,[25] F. Blanc,[25] V. Boisvert,[25] D. G. Cassel,[25] M. Dickson,[25] P. S. Drell,[25] K. M. Ecklund,[25] R. Ehrlich,[25] A. D. Foland,[25] P. Gaidarev,[25] L. Gibbons,[25] B. Gittelman,[25] S. W. Gray,[25] D. L. Hartill,[25] B. K. Heltsley,[25] P. I. Hopman,[25] C. D. Jones,[25] D. L. Kreinick,[25] M. Lohner,[25] A. Magerkurth,[25] T. O. Meyer,[25] N. B. Mistry,[25] E. Nordberg,[25] J. R. Patterson,[25] D. Peterson,[25] D. Riley,[25] J. G. Thayer,[25] D. Urner,[25] B. Valant-Spaight,[25] A. Warburton,[25] P. Avery,[26] C. Prescott,[26] A. I. Rubiera,[26] J. Yelton,[26] J. Zheng,[26] G. Brandenburg,[27] A. Ershov,[27] Y. S. Gao,[27] D. Y.-J. Kim,[27] R. Wilson,[27] T. E. Browder,[28] Y. Li,[28] J. L. Rodriguez,[28] and H. Yamamoto[28]

[1]University of Illinois, Urbana-Champaign, Illinois 61801
[2]Carleton University, Ottawa, Ontario, Canada K1S 5B6
and the Institute of Particle Physics, Canada
[3]McGill University, Montréal, Québec, Canada H3A 2T8
and the Institute of Particle Physics, Canada
[4]Ithaca College, Ithaca, New York 14850
[5]University of Kansas, Lawrence, Kansas 66045

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*Permanent address: University of Cincinnati, Cincinnati, OH 45221

†Permanent address: Massachusetts Institute of Technology, Cambridge, MA 02139.

[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]Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309
[13]Southern Methodist University, Dallas, Texas 75275
[14]Syracuse University, Syracuse, New York 13244
[15]University of Texas, Austin, TX 78712
[16]University of Texas - Pan American, Edinburg, TX 78539
[17]Vanderbilt University, Nashville, Tennessee 37235
[18]Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061
[19]Wayne State University, Detroit, Michigan 48202
[20]California Institute of Technology, Pasadena, California 91125
[21]University of California, San Diego, La Jolla, California 92093
[22]University of California, Santa Barbara, California 93106
[23]Carnegie Mellon University, Pittsburgh, Pennsylvania 15213
[24]University of Colorado, Boulder, Colorado 80309-0390
[25]Cornell University, Ithaca, New York 14853
[26]University of Florida, Gainesville, Florida 32611
[27]Harvard University, Cambridge, Massachusetts 02138
[28]University of Hawaii at Manoa, Honolulu, Hawaii 96822

I. INTRODUCTION

In the Standard Model the decays $B^0 \to e^+e^-$ and $B^0 \to \mu^+\mu^-$ are allowed via the diagrams shown in Fig 1. The Standard Model predictions for the branching fractions are $\mathcal{B}(B^0 \to e^+e^-) = 1.9 \times 10^{-15}$ and $\mathcal{B}(B^0 \to \mu^+\mu^-) = 8.0 \times 10^{-11}$, respectively [1]. These rates put them beyond the reach of current experiments. Their observation at CLEO would provide clear evidence for physics beyond the Standard Model.

In two Higgs doublet models, the corresponding branching fractions can be strongly enhanced due to additional diagrams involving Higgs bosons [2]. Supersymmetric particles can further modify the expectation, but calculations of SUSY contributions have not yet been made. In some models with Z-mediated flavor changing neutral currents [3] the corresponding branching fraction can be enhanced by a factor of 400 [4] compared to Standard Model predictions.

The decay $B^0 \to e^\pm\mu^\mp$ is forbidden in the Standard Model by lepton number conservation. However it can occur in Pati-Salam leptoquark models [5], due to the existence of particles that couple to both quarks and leptons.

Currently the best 90% confidence level limits on the branching fractions are $\mathcal{B}(B^0 \to e^+e^-) < 59 \times 10^{-7}$ (from CLEO [6]), $\mathcal{B}(B^0 \to e^\pm\mu^\mp) < 35 \times 10^{-7}$ (from CDF [7]) and $\mathcal{B}(B^0 \to \mu^+\mu^-) < 6.8 \times 10^{-7}$ (from CDF [8]).

II. DATA SAMPLE

We use data taken with the CLEO II/II.V detector [9] operating at the Cornell Electron Storage Ring (CESR). The sample consists of 9.1 fb^{-1} taken on the $\Upsilon(4S)$ resonance, corresponding to approximately 9.7×10^6 $B\bar{B}$ pairs. An additional sample of 4.5 fb^{-1} accumulated approximately 60 MeV below the $\Upsilon(4S)$ resonance is used to estimate the non-resonant background. Charge conjugation is implied throughout this paper and equal production of charged and neutral B mesons at the $\Upsilon(4S)$ resonance is assumed. The CLEO II charged particle tracking system consists of a 6-layer straw tube chamber, a 10-layer precision tracking chamber and a 51 layer main drift chamber. In the CLEO II.V configuration the straw tube chamber was replaced by a 3-layer, double-sided silicon tracker. Beyond the tracking chambers, but inside the 1.5T solenoid magnet, are a time-of-flight system and an electromagnetic calorimeter consisting of 7800 CsI crystals. Electron identification is performed with a likelihood function combining calorimeter (E/p, the ratio of energy deposited by particle in calorimeter to its momentum) and specific ionization (dE/dx) information. Muons are identified using proportional counters placed at various depths in the steel return yoke of the magnet.

Since, at a symmetric e^+e^- collider, B mesons at the $\Upsilon(4S)$ resonance are produced nearly at rest, the decays $B^0 \to e^+e^-$, $B^0 \to \mu^+\mu^-$ and $B^0 \to e^\pm\mu^\mp$ will contain two nearly back-to-back leptons with momenta $p \approx 2.6$ GeV. In order to select $B\bar{B}$ events, we require at least five charged tracks in the event with two well reconstructed and oppositely charged tracks identified as leptons. The lepton pair is required to have a mass within three standard deviations from the the mass of the B^0 meson. We use the beam constrained mass, $M(B) = \sqrt{E_{beam}^2 - (\vec{p}_{l^+} + \vec{p}_{l^-})^2}$. The resolution on $M(B)$ is 2.8 MeV for the $B^0 \to e^+e^-$

decay and 2.6 MeV for the $B^0 \to \mu^+\mu^-$ and $B^0 \to e^\pm\mu^\mp$ decays. For signal events, $M(B)$ is required to be within 3 standard deviations of the B^0 meson mass.

We calculate the energy difference between the candidate B^0 meson and the beam energy $\Delta E = E_{l^+} + E_{l^-} - E_{beam}$ and require that the difference should be $|\Delta E| < 75$ MeV for $B^0 \to \mu^+\mu^-$ decay, and for $B^0 \to e^+e^-$ and $B^0 \to e^\pm\mu^\mp$ decays it should satisfy -100 MeV $< \Delta E < 75$ MeV. The asymmetric ΔE requirement in $B^0 \to e^+e^-$ and $B^0 \to e^\pm\mu^\mp$ channels takes into account energy loss due to final state radiation from the electrons.

The main background comes from the processes $e^+e^- \to q\bar{q}(q = u, c, s, d)$ and $e^+e^- \to \tau^+\tau^-$. Such events usually exhibit a two jet structure and produce high momentum, approximately back-to-back tracks which satisfy the requirements imposed on our candidate events. We calculate the angle θ_T between the thrust axis of the B^0 candidate tracks and the thrust axis of the remaining charged and neutral tracks in the event. The distribution of $|\cos\theta_T|$ is flat for signal events and strongly peaked at 1 for background events. We require $|\cos\theta_T| < 0.9$.

III. SIGNAL SIMULATION

In order to take into account final state radiation (FSR) from the final state leptons, the matrix element for the decay $J/\psi \to e^+e^-(\gamma)$ from Ref. [10], modified in order to simulate $B^0 \to l^+l^-(\gamma)$ with $l^+l^- = e^+e^-, \mu^+\mu^-$ is included in the event generator. The detector simulation program is based on GEANT [11], the simulated events are processed as the data. The overall efficiencies for detecting the decays $B^0 \to e^+e^-$ and $B^0 \to \mu^+\mu^-$ are 37.3% and 46.2%, respectively, without FSR. Including FSR reduces these efficiencies to 31.1% and 42.4%, respectively. We use the efficiencies obtained with FSR included for the derivation of limits on branching fractions.

The efficiency for the decay $B^0 \to e^\pm\mu^\mp$ is 43.6% without FSR. There is no matrix element available for the decay $B^0 \to e^\pm\mu^\mp(\gamma)$. In this mode we use Monte Carlo without FSR. Since final state radiation reduces the efficiencies for $B^0 \to e^+e^-$ and $B^0 \to \mu^+\mu^-$ by 20% and 9%, respectively, we estimate the effect of FSR in $B^0 \to e^\pm\mu^\mp$ to be 15% and include this in the derivation of the upper limit on the branching fraction as a systematic uncertainty.

IV. RESULTS

The background from the process $e^+e^- \to q\bar{q}$ results from misidentification of hadrons as leptons and has been determined as follows. First, the analysis is redone without imposing the lepton identification requirements to determine the total number of 2-track events passing all other selection criteria in the signal and sideband regions (5.260 GeV $< M(B) <$ 5.270 GeV and $|\Delta E| < 200$ MeV) for both the on-resonance and off-resonance data samples. These are used to determine the expected number of events in the on-resonance signal region. (This is done by multiplying the number of events seen in the signal region in off-resonance data by the ratio of numbers of events seen in the sideband region in on- and off-resonance data.) The probabilities for these tracks to be identified as leptons is determined from the relative abundances of particles (π, K, proton, electron, muon) and the fake rates. The particle abundances for the B^0 candidate tracks in $q\bar{q}$ events have been determined using Monte Carlo and were found to be 0.58 for $\pi^{\pm}$, 0.25 for $K^{\pm}$, 0.15 for $p, \bar{p}$, and 0.004 for electrons and muons. For $\pi^{\pm}$ and $K^{\pm}$ the fake rates are determined experimentally from samples of $D^{*+} \to D^0\pi^+ \to K^-\pi^+\pi^+$ decays. Proton fake rates are taken from Monte Carlo. The expected number of backgrounds events from $e^+e^- \to q\bar{q}$ are 0.01 ± 0.01, 0.14 ± 0.03 and 0.09 ± 0.03 for the $ee, \mu\mu$ and $e\mu$ channels, respectively.

Backgrounds from $e^+e^- \to \tau^+\tau^-$ events are estimated using a Monte Carlo sample analyzed without lepton identification, using the procedure described above to determine the expected rate of events with the two candidate tracks identified as leptons. The particle abundances for the B^0 candidate tracks in simulated $\tau^+\tau^-$ events were found to be 0.74 for $\pi^{\pm}$, 0.04 for $K^{\pm}$, and 0.11 for electrons and muons. The expected numbers of background events are 0.10 ± 0.07 , 0.08 ± 0.06 and 0.40 ± 0.20 events for the ee, $\mu\mu$ and $e\mu$ channels, respectively. The background from $B\bar{B}$ events is estimated from Monte Carlo and is found to be less than 0.01 events in all modes.

We find no events in the signal regions for the e^+e^- and $\mu^+\mu^-$ modes and two events in the signal region for the $e^{\pm}\mu^{\mp}$ mode. These events are consistent with the expected background. To conservatively account for the uncertainty in the efficiency determination, we reduce the efficiency by the estimated systematic error of 7.6% in the e^+e^- and $\mu^+\mu^-$ modes and 16.3% in the $e^{\pm}\mu^{\mp}$ mode when calculating the upper limits. The latter error is dominated by the uncertainty from final state radiation. A summary of the efficiencies, event yields and limits is given in Table I.

TABLE I. Summary of results and branching fraction upper limits. N_{exp} is the number of expected background events, N_{obs} is the number of events observed, N_{UL} is the number of events corresponding to a 90% CL limit, and ϵ is the detection efficiency. The first quoted error on ϵ is statistical while the second is systematic.

mode	N_{exp}	N_{obs}	N_{UL}	ϵ	Upper limit
$B^0 \to e^+e^-$	0.11 ± 0.07	0	2.30	31.1±0.4±2.4%	8.3×10^{-7}
$B^0 \to \mu^+\mu^-$	0.22 ± 0.07	0	2.30	42.4±0.5±3.2%	6.1×10^{-7}
$B^0 \to e^{\pm}\mu^{\mp}$	0.49 ± 0.20	2	5.24	43.6±0.5±7.1%	14.9×10^{-7}

V. LIMITS ON PATI-SALAM LEPTOQUARKS

One of the simplest models that assumes symmetry between quarks and leptons is the Pati-Salam model [5]. This model predicts heavy spin-one gauge bosons, called leptoquarks (LQ), that carry both color and lepton quantum numbers. While most leptoquark models assume that the leptoquarks couple within one generation only, Pati-Salam model allows cross-generation couplings. Consequently, Pati-Salam leptoquarks can mediate the decay

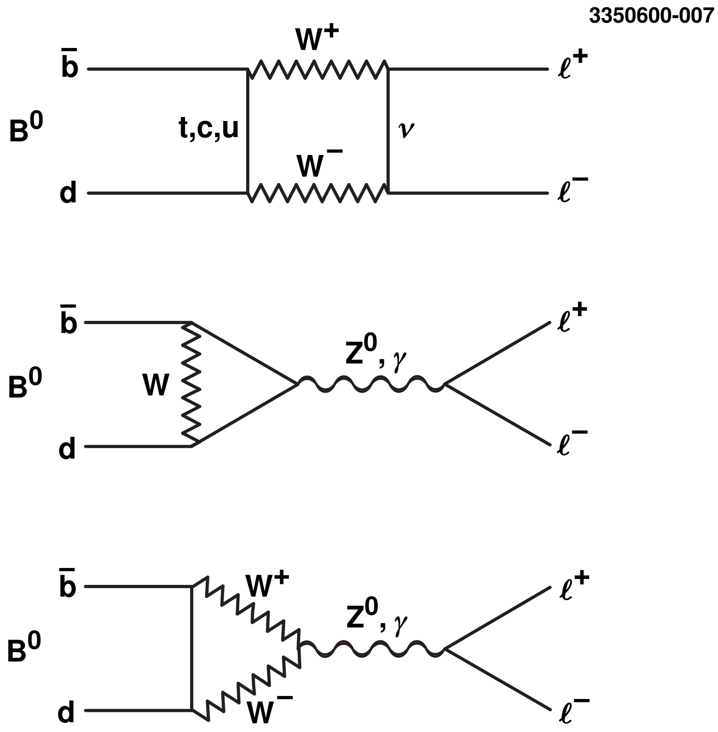

FIG. 1. Feynman diagrams for the decay $B^0 \to l^+l^-$ $(l = e, \mu)$ in the Standard Model.

$B^0 \to e^\pm\mu^\mp$ [12,13]. The relationship between $\mathcal{B}(B^0 \to e^\pm\mu^\mp)$ and leptoquark mass is [13]

$$\Gamma(B^0 \to e^\pm\mu^\mp) = \pi\alpha_s^2(M_{LQ})\frac{1}{M_{LQ}^4}F_{B^0}^2 m_{B^0}^3 R^2$$

where

$$R = \frac{m_{B^0}}{m_b}\Big(\frac{\alpha_s(M_{LQ})}{\alpha_s(m_t)}\Big)^{-\frac{4}{7}}\Big(\frac{\alpha_s(m_t)}{\alpha_s(m_b)}\Big)^{-\frac{12}{23}}.$$

The first attempt to constrain the Pati-Salam leptoquark masses by measuring the branching fraction for $B^0 \to e^\pm\mu^\mp$ was made by the CDF collaboration [7]. The result obtained was $M_{LQ} > 21.7$ TeV. We follow the CDF procedure by using $F_B = 175 \pm 30$ MeV for B^0 decay constant [14], $m_{B^0} = 5279.1 \pm 0.7(\text{stat.}) \pm 0.3(\text{syst.})$ MeV [16], $m_t = 176.0 \pm 6.5$ GeV [15] and obtain a new limit on the Pati-Salam leptoquark mass of $M_{LQ} > 27$ TeV at 90% confidence level.

In conclusion we find no evidence for the decays $B^0 \to e^+e^-, \mu^+\mu^-$ and $e^\pm\mu^\mp$ and obtain upper limits on the corresponding branching fractions of $\mathcal{B}(B^0 \to e^+e^-) < 8.3 \times 10^{-7}$, $\mathcal{B}(B^0 \to \mu^+\mu^-) < 6.1 \times 10^{-7}$, $\mathcal{B}(B^0 \to e^\pm\mu^\mp) < 15 \times 10^{-7}$ at 90% confidence level. The limit on $\mathcal{B}(B^0 \to e^\pm\mu^\mp)$ corresponds to a lower limit of 27 TeV on the Pati-Salam leptoquark mass at 90% CL.

We gratefully acknowledge the effort of the CESR staff in providing us with excellent luminosity and running conditions. I.P.J. Shipsey thanks the NYI program of the NSF,

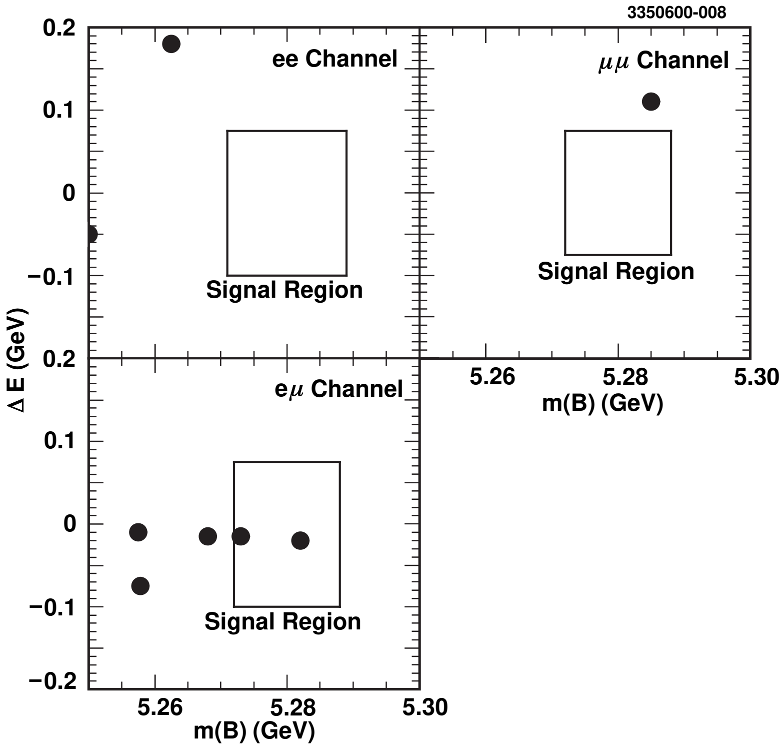

FIG. 2. Beam constrained mass of dilepton pair vs energy difference $\Delta E = E_{l^+} + E_{l^-} - E_{beam}$ for on resonance data. All selection criteria except the requirements on lepton pair mass and ΔE are included. The box in the center of each plot shows the signal region.

M. Selen thanks the PFF program of the NSF, M. Selen and H. Yamamoto thank the OJI program of DOE, M. Selen and V. Sharma thank the A.P. Sloan Foundation, M. Selen and V. Sharma thank the Research Corporation, F. Blanc thanks the Swiss National Science Foundation, and H. Schwarthoff and E. von Toerne thank the Alexander von Humboldt Stiftung for support. This work was supported by the National Science Foundation, the U.S. Department of Energy, and the Natural Sciences and Engineering Research Council of Canada.

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