

## Semi-inclusive $\Lambda$ and $K_S$ Production in $p$ -Au Collisions at 17.5 GeV/ $c$

I. Chemakin,<sup>2</sup> V. Cianciolo,<sup>7,8</sup> B. A. Cole,<sup>2</sup> R. Fernow,<sup>1</sup> A. D. Frawley,<sup>3</sup> M. Gilkes,<sup>9</sup> S. Gushue,<sup>1</sup> E. P. Hartouni,<sup>7</sup> H. Hiejima,<sup>2</sup> M. Justice,<sup>5</sup> J. H. Kang,<sup>11</sup> H. Kirk,<sup>1</sup> N. Maeda,<sup>3</sup> R. L. McGrath,<sup>9</sup> S. Mioduszewski,<sup>10</sup> D. Morrison,<sup>10,1</sup> M. Moulson,<sup>2</sup> M. N. Nambodiri,<sup>7</sup> G. Rai,<sup>6</sup> K. Read,<sup>10</sup> L. Remsberg,<sup>1</sup> M. Rosati,<sup>1,4</sup> Y. Shin,<sup>11</sup> R. A. Soltz,<sup>7</sup> S. Sorensen,<sup>10</sup> J. H. Thomas,<sup>7,6</sup> Y. Torun,<sup>9,1</sup> D. Winter,<sup>2</sup> X. Yang,<sup>2</sup> W. A. Zajc,<sup>2</sup> and Y. Zhang<sup>2</sup>

<sup>1</sup>Brookhaven National Laboratory, Upton, New York 11973

<sup>2</sup>Columbia University, New York, New York 10027

<sup>3</sup>Florida State University, Tallahassee, Florida 32306

<sup>4</sup>Iowa State University, Ames, Iowa 50010

<sup>5</sup>Kent State University, Kent, Ohio 44242

<sup>6</sup>Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720

<sup>7</sup>Lawrence Livermore National Laboratory, Livermore, California 94550

<sup>8</sup>Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831

<sup>9</sup>State University of New York at Stony Brook, Stony Brook, New York 11794

<sup>10</sup>University of Tennessee, Knoxville, Tennessee 37996

<sup>11</sup>Yonsei University, Seoul 120-749, Korea

(Received 5 April 2000)

The first detailed measurements of the centrality dependence of strangeness production in  $p$ -A collisions are presented.  $\Lambda$  and  $K_S$   $dn/dy$  distributions from 17.5 GeV/ $c$   $p$ -Au collisions are shown as a function of “grey” track multiplicity and the estimated number of collisions,  $\nu$ , made by the proton. The  $\nu$  dependence of the  $\Lambda$  yield deviates from a scaling of  $p$ - $p$  data by the number of participants, increasing faster than this scaling for  $\nu \leq 5$  and saturating for larger  $\nu$ . A slower growth in  $K_S$  multiplicity with  $\nu$  is observed, consistent with a weaker  $\nu$  dependence of  $K\bar{K}$  production than  $YK$  production.

PACS numbers: 25.75.Dw, 13.85.Ni, 25.40.Ve

Significant effort has been devoted in the last decade to measuring strange particle production in nucleus-nucleus ( $A$ - $A$ ) collisions, motivated by predictions that quark-gluon plasma (QGP) formation could enhance strangeness [1,2]. Experiments at both the Brookhaven National Laboratory (BNL) Alternative Gradient Synchrotron (AGS) and the CERN Super Proton Synchrotron (SPS) accelerators have reported large increases in relative strange particle yields in central light (Si, S) [3–6] and heavy ion (Au, Pb) [7–11] induced collisions compared to  $p$ - $p$  collisions. However, we still cannot claim a true understanding of the physics of strangeness enhancement due to the complexity of the hadronic interactions underlying  $A$ - $A$  collisions and the competing mechanisms proposed and/or used in models [12–14] to explain the data.

The difficulty in interpreting the  $A$ - $A$  data and the observation that the enhancement is already present in light-ion collisions suggest the use of  $p$ - $A$  collisions to study this problem further. The simpler final state of  $p$ - $A$  collisions may allow the production rate for strange particles to be directly connected with the scattering dynamics of the incoming proton. Previously published  $p$ - $A$  data [15,16] demonstrated an increase in the inclusive  $K/\pi$  ratio with increasing  $A$  at the AGS, suggesting that the strangeness enhancement mechanism is already at work in  $p$ - $A$  collisions. A more thorough analysis [17] of inclusive data at higher energies [18] suggested no overall strangeness enhancement but a possible modest enhancement in  $\Lambda$  production offset by a decrease in  $\bar{K}$  production. This result

has led to claims that the observed strangeness enhancement in  $A$ - $A$  collisions at SPS energies may result from QGP formation [19]. However, extrapolations to central  $A$ - $A$  data from *inclusive*  $p$ - $A$  data are intrinsically flawed: Centrally selected  $A$ - $A$  events necessarily involve more scatterings of the participant nucleons, and the dynamics of strangeness production may be quite sensitive to these additional scatters. A resolution of this problem requires a detailed measurement of the centrality dependence of strangeness production in  $p$ - $A$  collisions.

In this paper we present the first such measurement, made by BNL experiment 910 at the AGS accelerator. The data consist of  $\Lambda$  and  $K_S$  rapidity spectra and integrated yields obtained as a function of “grey” track multiplicity from  $p$ -Au collisions at a beam momentum of 17.5 GeV/ $c$ . E910’s nearly complete rapidity coverage allows us to accurately estimate the total  $\Lambda$  and  $K_S$  multiplicities and study the variation of absolute yields with  $\nu(N_{\text{grey}})$ , the estimated number of collisions of the proton in the Au nucleus. A common benchmark [4,11,20] for evaluating strangeness enhancement in  $A$ - $A$  collisions is the scaling of  $p$ - $p$  data by the number of participants,  $N_{\text{part}}$ , in the collision. For  $p$ - $A$  collisions, an  $N_{\text{part}}$  scaling of  $p$ - $p$  data would yield [21]

$$N_{\text{prod}} = \frac{1}{2} N_{\text{prod}}^{pp} (1 + \nu), \quad (1)$$

since there are two participants in  $p$ - $p$  collisions. We compare our multiplicities to the yields expected from Eq. (1)

to evaluate whether we see enhanced strange particle production using the same benchmark as in  $A$ - $A$  collisions. We observe that for  $\Lambda$  production Eq. (1) is physically sensible since the baryon number is conserved and  $B\bar{B}$  processes are negligible at our energies. Deviations from Eq. (1) would imply contributions from target nucleons not directly struck by the projectile or changes in the probability of participants to fragment into  $\Lambda$ 's.

E910 was staged in the Multi-Particle Spectrometer (MPS) facility at the AGS. For these data, the Cherenkov tagged secondary proton beam had a mean momentum of  $17.5 \pm 0.1$  GeV/ $c$  and a 1.5% momentum spread. The E910 spectrometer was previously described in [22]; the results presented here rely on the Equation of State time projection chamber (TPC) and the beam line/trigger counters. A 3.9 g/cm<sup>2</sup> Au target was located 20.5 cm upstream of the active area of the TPC and was immediately followed by a 10 cm  $\times$  10 cm two-layer scintillating-fiber hodoscope. This multiplicity detector provided two triggers, a minimum-bias (MB) trigger that required 2 hits on each layer and a "central" trigger that required a total of 20 hits in the two layers and selected approximately the 25% most central events. Because of the low light yield of the fibers the MB trigger suffered significant efficiency loss for low multiplicity events with no highly ionizing tracks.

After finding and fitting the recorded pulses in the TPC we obtained typical resolutions of 0.7 mm (vertical) and 0.5 mm (horizontal) for position measurements in each sample. The momentum resolution for particles bending in the 0.5 T magnetic field varied from 1.2% ( $p < 2$  GeV/ $c$ ) to 5.5% ( $p \sim 17$  GeV/ $c$ ). The  $dE/dx$  measurement, obtained from a truncated mean of the TPC samples on each track, provided a resolution of  $\sigma/\langle dE/dx \rangle = 6\%$  for typical track lengths.  $\Lambda$ 's and  $K_S$ 's were measured and identified through a combination of topological reconstruction and  $dE/dx$  identification of the decay daughters. We paired and removed conversion electrons and positrons, the dominant source of background, with an efficiency of  $\approx 50\%$ . We further reduced background from conversions and from false vertices by applying tighter geometric cuts to small opening-angle pairs. We attempted topological fits on  $+/-$  track pairs satisfying applied geometric and  $dE/dx$  cuts and accepted as  $V_0$  candidates those passing applied  $\chi^2$  cuts with origin  $\geq 3.5$  cm from the target. We

used a combined likelihood from the single track  $dE/dx$ 's and hypothetical  $p\pi^-$  and  $\pi^+\pi^-$  invariant masses ( $M_{\text{inv}}$ ) of the pairs to identify the decaying particle, obtaining the  $M_{\text{inv}}$  distributions shown in Fig. 1. We obtained mass resolutions of FWHM = 4 MeV and 13 MeV for  $\Lambda$ 's and  $K_S$ 's, respectively, and corresponding  $S/B$  ratios of 35:1 and 30:1. The acceptances were calculated via GEANT simulations of the detector response to 20M pure  $\Lambda$  and 10M pure  $K_S$  decays [23]. We show in Fig. 1 the  $y$ - $p_\perp$  regions with  $>10\%$  acceptance. For the centrality measurement, we identified as grey tracks protons and deuterons in the momentum ranges [0.25, 1.2] GeV/ $c$  and [0.5, 2.4] GeV/ $c$ , respectively. We obtain the multiplicity of grey tracks,  $N_{\text{grey}}$ , within our geometric acceptance event by event and from this quantity estimate the mean number of collisions suffered by the beam proton,  $\bar{v}(N_{\text{grey}})$ , using an established technique [22].

The data presented in this paper resulted from combined 4.65M triggers. We required a valid event to have at least one secondary charged particle in the final state and a  $\Sigma p_\perp > 85$  MeV/ $c$ . In addition, we vetoed one- and two-track events containing a high-momentum positive track consistent with a quasielastically scattered proton. After applying quality and the above interaction cuts we obtained 2.97M events, 1.88M minimum-bias, and 2.07M central. From these, we reconstructed a total of 156.8k  $\Lambda$ 's and 76.8k  $K_S$ 's. Using beam-triggered events we determined trigger efficiency corrections as a two-dimensional function of charged-particle multiplicity and  $N_{\text{grey}}$ . The correction for multiplicity 1,2 events with  $N_{\text{grey}} = 0$  is large (5.1) while the average correction for all interactions is 1.1.

We calculated  $\Lambda$  and  $K_S$  yields  $\Delta N(m_\perp, y, M_{\text{inv}})$  per event as a function of  $N_{\text{grey}}$  after subtracting the  $\Lambda$  and  $K_S$  background in each bin. We corrected these for acceptance ( $A$ ), trigger efficiency ( $\epsilon$ ), and branching ratio (BR) to obtain an invariant differential yield,

$$\frac{d^2 n_{\Lambda/K_S}}{m_\perp dm_\perp dy} = \frac{1}{m_\perp} \frac{1}{A\epsilon\text{BR}} \frac{\Delta N_{\Lambda/K_S}(m_\perp, y)}{N_{\text{evt}} \Delta m_\perp \Delta y}. \quad (2)$$

For  $N_{\text{grey}} < 4$ , we used only MB triggers, but for larger  $N_{\text{grey}}$  we combined both triggers, weighting by the number of events in each sample. The  $m_\perp$  spectra are uniformly well described by exponential distributions except at the

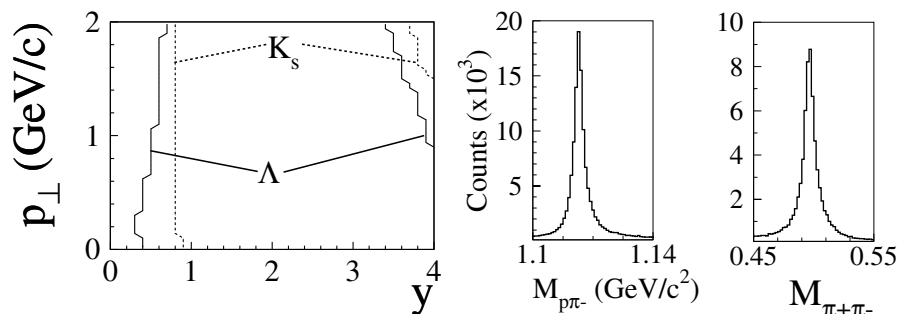


FIG. 1.  $\Lambda$  and  $K_S$  acceptance boundary (left) and reconstructed invariant mass spectra (right).

highest  $m_{\perp}$  values ( $m_{\perp} - m > 0.6$  at midrapidity) where we do not have sufficient statistics to accurately determine the background subtraction. We fit the  $m_{\perp}$  spectra excluding these points to the form

$$\frac{1}{2\pi m_{\perp}} \frac{d^2n}{dm_{\perp} dy} = \frac{1}{2\pi(m_0 + T)T} \frac{dn}{dy} e^{-(m_{\perp}-m_0)/T}, \quad (3)$$

where  $dn/dy$  is a direct parameter of the fit representing the integral of Eq. (3) over  $m_{\perp}$ . The fits give inverse slopes,  $T$ , that vary from 0.05 GeV/c at low and high  $y$  to 0.14 GeV/c at midrapidity, consistent with proton spectra obtained from  $p$ - $A$  collisions at a similar energy [16]. For  $N_{\text{grey}}$  bins where we do not have enough statistics to perform the fits we directly sum over  $m_{\perp}$  to obtain  $dn/dy$ . Figure 2 shows the resulting  $dn/dy$  distributions for a subset of the available  $N_{\text{grey}}$  bins. We estimate 90% C.L. point-to-point systematic errors in the  $\Lambda$  and  $K_S$   $dn/dy$  measurements, including contributions from the fitting, to be  $<5\%$  except for the lowest rapidity bin (20%), and estimate the normalization systematic error to be  $\pm 10\%$ .

We observe that, with increasing  $N_{\text{grey}}$ , the  $\Lambda$  and  $K_S$  yields decrease at high rapidity and increase at low rapidity. For  $\Lambda$ 's, the decrease in yield at large rapidity is a direct consequence of the increased "stopping" of the projectile baryon resulting from the multiple interactions in the target nucleus. The strong increase in production of strange particles at low rapidity is qualitatively consistent with previously observed trends in secondary particle production in  $p$ - $A$  collisions [16,24,25]. We show in Fig. 3 the integrated yields that we have obtained by summing our measured  $dn/dy$  values as a function of  $\nu$ . The error on the in-acceptance yield is dominated by and taken to be the same as our uncertainty in the absolute normalization

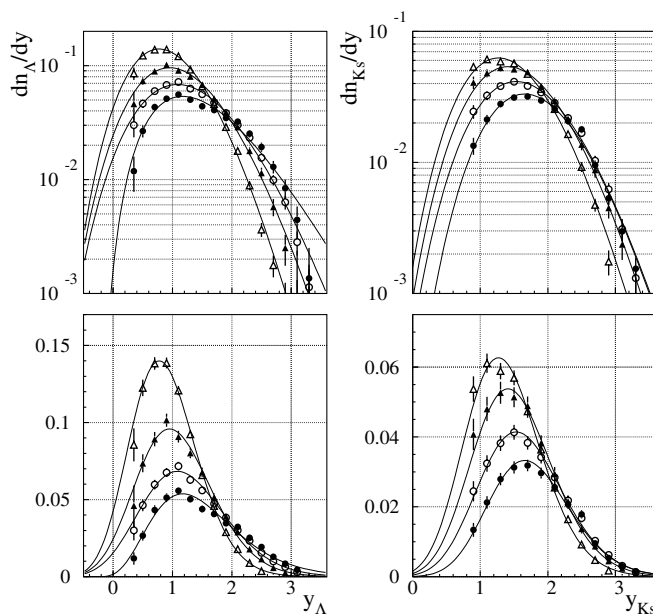


FIG. 2.  $\Lambda$  (left) and  $K_S$  (right) rapidity density distributions for different  $N_{\text{grey}}$  plotted in both log (top) and linear (bottom) scale.  $N_{\text{grey}} = 0$  (filled circle), 1 (open circle), 2 (filled triangle), and 4 (open triangle).

$\pm 10\%$  at 90% C.L. We show (solid line) in Fig. 3 the expectations from Eq. (1) with  $N_{pp}^{\Lambda} = 0.054 \pm 0.002(\text{syst})$  and  $N_{pp}^{K_S} = 0.035 \pm 0.002(\text{syst})$  obtained by parametrizing the  $\sqrt{s}$  dependence of  $\Lambda$  and  $K_S$  multiplicities [26] and interpolating to our energy. The  $\Lambda$  yields initially increase faster with  $\nu$  than expected from the  $N_{\text{part}}$  scaling of  $p$ - $p$  yields and then saturate and start to decrease. The  $K_S$  yields behave similarly with a slower initial increase. The apparent decrease of the yields may result from the fact that we miss a larger fraction of the total  $\Lambda$  and  $K_S$  yield with increasing  $N_{\text{grey}}$  or  $\nu$  due to our low-rapidity cutoff. We have estimated the missing yield by fitting the  $dn/dy$  distributions to gamma distributions as shown in Fig. 3 and extrapolating these into the unmeasured region to produce the estimated total yields shown in Fig. 3. The uncertainty in the total yield is largest for the larger  $N_{\text{grey}}$  or  $\nu$  bins where the  $dn/dy$  distribution peaks near the edge of our acceptance. We show in Fig. 3 90% C.L. systematic errors on the yields with larger errors on the high side to account for the possibility that an unknown mechanism may produce a larger  $\Lambda$  yield below  $y = 0$  than we estimate. The resulting total  $\Lambda$  yields shown in Fig. 3 saturate at large  $\nu$  and remain flat. We have fit the extrapolated  $\Lambda$  yields to an empirical function,

$$N_{\Lambda} = N_{pp}^{\Lambda} (1 - e^{-\kappa\nu^{\alpha}}) / (1 - e^{-\kappa}), \quad (4)$$

where  $N_{pp}$  is the  $\Lambda$  multiplicity in  $p$ - $p$  collisions. The obtained function with  $\kappa = 0.299 \pm 0.008$  and  $\alpha = 1.29 \pm 0.03$  describes both the initial rapid rise of the yield and the saturation at large  $\nu$ . To evaluate the significance of this fast initial increase in the  $\Lambda$  yield we plot in Fig. 3 the yield that would result from a "binary-collision" (BC) scaling of  $p$ - $p$  data,

$$N^{\text{BC}}(\nu) = N_{pp}\nu, \quad (5)$$

which we view as the fastest plausible increase that could be expected from the multiple scattering of the incoming proton. The  $\Lambda$  yields are consistent with this "upper limit" for  $\nu \leq 3$  indicating a rate of increase in  $\Lambda$  yield with  $\nu$  in this region that is approximately twice that given by

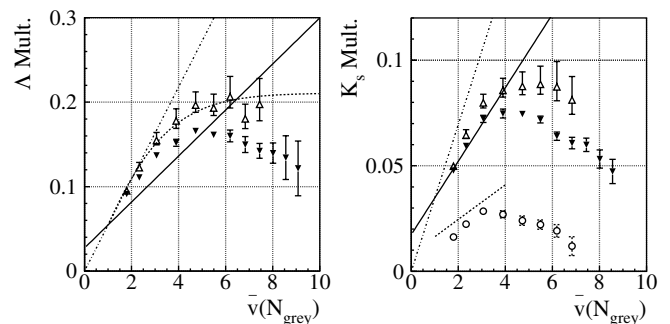


FIG. 3.  $\Lambda$  (left) and  $K_S$  (right) multiplicities vs  $\bar{\nu}(N_{\text{grey}})$ . Solid triangle: in E910 acceptance; open triangle: total yield (systematic errors from extrapolation included); circle: estimated  $\bar{K}^0$  component of  $K_S$ ; solid line:  $N_{\text{part}}$  scaling; dash-dotted line: binary collision; dashed line: empirical fit to  $\Lambda$  (left panel; see text for details), estimated  $N_{\text{part}}$  scaling for  $\bar{K}^0$  (right panel).

Eq. (1). We note that the systematic error on the  $\nu$  scale of  $\pm 15\%$  [22] is small compared to this difference in slope.

We observe that the  $K_S$  yield increases more slowly with  $\nu$  than the  $\Lambda$  yield and appears to decrease slightly at large  $\nu$  even after we have accounted for the missing yield. The difference in behavior between the  $\Lambda$  and  $K_S$  yields may result from the mixture of  $K^0$  and  $\bar{K}^0$  in the  $K_S$  and the fact that these are produced through different processes. In  $p$ - $p$  collisions at comparable energies,  $\frac{1}{2}$  of the  $K_S$  are produced as  $K^0$ 's in association with hyperons with the other half produced as  $\bar{K}^0$ 's associated with kaons [27]. If we assume that this proportion is not modified in  $p$ - $A$  collisions and that the total hyperon yields increase in proportion to the  $\Lambda$  yield, we can estimate the  $\bar{K}^0$  component of the measured  $K_S$  yields shown in Fig. 3. The  $\bar{K}^0$  component appears to increase by a factor of 2 at  $\nu = 3$ , roughly consistent with the  $N_{\text{part}}$  scaling of  $p$ - $p$  data shown in Fig. 3, before starting to decrease slowly with  $\nu$ . While our data suggest an increase in  $K\bar{K}$  production with  $\nu$ , because of uncertainties in the above assumptions we cannot make a stronger statement. A forthcoming analysis of  $K^-$  production will provide clearer insight into this problem.

In conclusion, we have reported on the first detailed investigation of the centrality dependence of strange particle production in  $p$ - $A$  collisions using grey track multiplicity and the estimated number of collisions of the projectile nucleon to characterize centrality. We have measured  $dn/dy$  distributions for  $\Lambda$  and  $K_S$  that both show a strong backward shift with increasing  $N_{\text{grey}}$  and  $\nu$ . The estimated total  $\Lambda$  yields increase with  $\nu$  at a rate approximately twice that expected from the  $N_{\text{part}}$  scaling of  $p$ - $p$  data for  $\nu \leq 3$  and saturate for  $\nu > 5$ . As noted above, this violation of  $N_{\text{part}}$  scaling implies either that additional nucleons not directly struck by the projectile contribute to  $\Lambda$  production or that the probability for one or more of the participants to fragment into a  $\Lambda$  increases with  $\nu$ . We observe a slower but significant increase in  $K_S$  multiplicity with  $\nu$  that apparently results from different behavior of the  $K^0$  and  $\bar{K}^0$  components of the  $K_S$ . The observed increase in  $K_S$  yield is large enough to allow for a statistically significant increase in  $K\bar{K}$  production with  $\nu$  for  $\nu \leq 3$  using a reasonable extrapolation of  $p$ - $p$  data.

We conclude that at AGS energies  $p$ - $A$  data show a clear violation of a simple  $N_{\text{part}}$  scaling of  $p$ - $p$  data. This result has clear qualitative implications for use of such scaling for interpreting strangeness yields in  $A$ - $A$  collisions. To quantitatively evaluate the potential implications of our results, we assume that the target contribution to the  $p$ - $Au$   $\Lambda$  yield grows as  $\nu N_{pp}/2$  and attribute the remainder to the fragmentation of the projectile and/or energy deposition of the projectile in the nucleus. Then, our data show that the "projectile" contribution increases proportional to  $\nu$  for  $\nu \leq 3$  with a slope that is the same as for the target nucleons. In  $A$ - $A$  collisions where *both* the projectile and target nucleons multiply scatter, this picture implies that the hyperon and associated kaon yields per participant would increase rapidly with the average number of scatters of the

participants,  $\langle \nu \rangle$ , for  $\langle \nu \rangle \leq 3$  giving a maximum possible increase in yield per participant of a factor  $\sim 3$ . This is precisely the behavior seen in the  $K^+$  production in Si-Au and Au-Au collisions at the AGS [4] and  $\Lambda$  production in Pb-Pb collisions at the SPS [11]. In  $p$ - $A$  collisions, the enhancement is more modest—a 50% increase over  $N_{\text{part}}$  scaling at  $\nu = 3$ —simply because the target nucleons scatter only once. As we have shown, however, this modest enhancement may have profound consequences for interpretation of the strangeness enhancement in nuclear collisions. We note that the above picture is consistent with the additive quark model [28] used by Kadija *et al.* [29] to explain the observed strangeness enhancement in light-ion collisions at the SPS. In particular, the increase in the projectilelike component up to  $\nu = 3$  is exactly what is expected from the additive quark model. Since the saturation of the  $\Lambda$  yield for  $\nu > 5$  is very likely due to the stopping of the incident baryon we predict that at higher energies the  $\Lambda$  yield will continue to increase for  $\nu > 5$ .

We thank Dr. R. Hackenburg and the MPS staff, J. Scuduto, and Dr. G. Bunce. This work has been supported by the U.S. Department of Energy under contracts with BNL (DE-AC02-98CH10886), Columbia (DE-FG02-86ER40281), ISU (DOE-FG02-92ER4069), KSU (DE-FG02-89ER40531), LBNL (DE-AC03-76F00098), LLNL (W-7405-ENG-48), ORNL (DE-AC05-96OR22464), and UT (DE-FG02-96ER40982) and the National Science Foundation under contract with FSU (PHY-9523974).

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