Dielectron Cross Section Measurements in Nucleus-Nucleus Reactions at 1.0*A* GeV

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We present measured dielectron production cross sections for Ca + Ca, C + C, He + Ca, and d + Ca reactions at 1.0 A GeV. Statistical uncertainties and systematic effects are smaller than in previous dilepton spectrometer (DLS) nucleus-nucleus data. For pair mass $M \leq 0.35$ GeV/c^2 we obtain (1) the Ca + Ca cross section is larger than the previous DLS measurement and current model results, (2) the mass spectra suggest large contributions from π^0 and η Dalitz decays, and (3) $d\sigma/dM \propto A_P A_T$. For $M > 0.5$ GeV/c^2 the Ca + Ca to C + C cross section ratio is significantly larger than the ratio of $A_P A_T$ values. [S0031-9007(97)03731-9]

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Dielectrons produced in heavy-ion collisions are attractive probes for studying dynamical properties of nucleus-nucleus interactions. The e^+e^- pairs do not undergo significant rescattering in the reaction, thus the kinematics of the pairs retains information about their production. This is of particular interest if the e^+e^- pairs are produced by processes, such as pion annihilation, that must occur during the hot, dense phase of the collisions. The use of this probe has produced interesting results at both Bevalac [1] and Super Proton Synchrotron (SPS) [2] energies. We present in this Letter the latest measurements of dielectron production from the Dilepton Spectrometer (DLS) Collaboration in nucleus-nucleus reactions at a beam kinetic energy of 1.0 A GeV.

The DLS Collaboration has previously reported on dielectron production in several colliding systems [1,3,4]. The "first generation" DLS data [1,3] from p + Be, Ca + Ca, and Nb + Nb reactions provided the first observations of dielectrons produced at Bevalac energies. Early calculations suggested that such data could be dominated by contributions from $\pi^+\pi^-$ annihilation [5,6]. Subsequent models of AA collisions in this energy regime [7–9] calculated that e^+e^- pairs of invariant mass below about 0.4 GeV/c^2 are produced primarily from conventional hadronic sources, such as pn bremsstrahlung and Dalitz decay processes (π^0, Δ, and η), but that contributions from $\pi^+\pi^-$ annihilation were needed to explain the Ca + Ca data at higher pair masses. Models that focus on density induced changes in the ρ-meson mass provide alternative descriptions of the pair yield at the higher masses [10,11]. Within the limited statistics of the first generation DLS data, it was not possible to distinguish among the models that provided results for specific DLS measurements.

After improvements to the DLS apparatus [13–15], a second generation of measurements was obtained: first from $p + p$ and $p + d$ reactions at a number of energies [4] and then from the Ca + Ca, C + C, He + Ca, and d + Ca reactions presented in this Letter. Each of these data sets contain significantly more pairs than earlier DLS data [1,3]. To increase our sensitivity to the effects of multiple hadronic interactions (e.g., $\pi^+\pi^-$ annihilation and multistep resonance excitation), the nucleus-nucleus reactions were chosen to have different numbers of participant nucleons but identical isospin and similar internal nuclear motion.

A description of the DLS apparatus has been published [13], and the analysis procedures used here are discussed in Ref. [14]. The new procedures lead to a mass-independent mass resolution for these data of $\sigma_M/M = 0.1$, and a new shape of the DLS acceptance boundary for $M \leq 0.2$ GeV/c^2. No explicit requirement on impact parameter (e.g., multiplicity) is imposed on these data. The cross sections presented here are evaluated in a three-dimensional, binned array of invariant mass (M), transverse momentum (p_t), and laboratory rapidity (y). (The DLS acceptance is approximately bounded by M from 0.05 to 1.25 GeV/c^2, p_t from 0.0 to 0.8 GeV/c, and laboratory rapidity from 0.5 to 1.9.) The data are available from the authors both as 3D tables and as projected spectra. A corresponding filter, which is necessary for comparisons with theoretical results and different from filters used for other data sets, is also available.

Early in the second generation of the DLS program, measurements showed a previously unrecognized trigger inefficiency due to instantaneous rates much larger than the well-controlled average rates. The microscopic duty factor of the beam, the instantaneous rates, and inefficiency varied on a time scale of hours. The efficiency could be reliably monitored only by the yield of the pairs themselves. A reanalysis of the first generation 4.9 GeV $p + \mathrm{Be}$ data found a correction factor of ~ 5 for the rate-dependent losses [16]. Because of the unstable nature of this problem, it is unwarranted to assume that other first generation DLS data have the same correction factor. Although they do show evidence for significant rate-dependent inefficiencies, they lack sufficient information for the calculation of appropriate correction factors. We suggest that the first generation data no longer be used for comparison with theory. In the second generation data, the rate-dependent losses were greatly reduced by improvements to the electronics and the beam monitoring systems. For each data set, we measured the rate dependence of the pair yield to permit extrapolation to zero rate. After these improvements, a measurement of the differential cross section for $p + p$ elastic scattering at 1.27 GeV (made concurrently with acquisition of $p + p$ dielectron data) produced results in agreement with the known cross section [17] and gave rate-dependent inefficiencies of $\leq 15\%$. In the dielectron data reported here, run-by-run corrections for such losses ranged between 10%–45%.

Table I lists the data sets with the corresponding beam energies, pair statistics, and absolute normalization uncertainties. The uncertainties are dominated by variations that result from using several methods to calculate the corrections for the rate-dependent efficiency. Cross sections were calculated from a single correction method, thus, when comparing two data sets, the appropriate relative uncertainty is $\sim 10\%$–15%.

The mass dependence of the differential cross sections is shown in Fig. 1. The systematic errors that are relevant to the shape of the spectra are displayed in this figure as added linearly to the statistical errors. These point-by-point systematics are independent of the normalization errors given in Table I. They are obtained from studies of the combinatoric background and studies of those acceptance corrections that were made in regions of phase space where the acceptance changes rapidly. Other effects, such as hadron contamination of the e^+e^- sample, are negligible compared to the systematics shown. (Henceforward we refer always to results within the DLS acceptance.)

Figure 1(a) displays the present data for the Ca + Ca cross section and the results of several calculations. The dotted line is from a Boltzmann-Uehling-Uhlenbeck (BUU) model [9] and shows the general trend of models that adequately represent our first generation Ca + Ca data. For the present data the integrated cross section ($M > 0.2$ GeV$/c^2$) is ~ 7 times larger than both the earlier data [1] and the model results. Most of the increase occurs for $M < 0.6$ GeV$/c^2$. We attribute the difference between our two measurements to the uncorrected trigger inefficiency of the first generation DLS data. The agreement between models and the present data remains reasonable above 0.6 GeV$/c^2$. In the mass range 0.2–0.4 GeV$/c^2$, however, the models predict pair yields that are dominated by Δ and η Dalitz decays but are significantly lower than our measurement. The shape of the yield is nonetheless quite similar to that of the η component of the BUU model shown in the dashed curve.

To emphasize the information contained in the spectrum shape, we have used a simple model of π^0 and η production to calculate the mass spectra of the Dalitz decays. (Details of the model are discussed below.) The shapes of these spectra are insensitive to reasonable choices of parameters in the model, and the shape of the η spectrum from this model is in good agreement with that component of the BUU model. Fitting the Ca + Ca data ($0.05 \leq M \leq 0.375$ GeV$/c^2$) with adjustable amplitudes of these two shapes yields the dashed curve shown in Fig. 1(a), with $P(\chi^2_\nu) \simeq 5\%$. The low probability of this fit may be due to the contributions from other sources (such as bremsstrahlung or Dalitz decays of baryon resonances). The overall agreement between curve and data shows that in this mass range the summed yield of pairs from those sources is either similar in shape to that from the π^0 and η mesons, relatively small, or slowly varying.

As shown by the solid curves in the other panels of Fig. 1, the other data sets also are well represented (for $0.05 \leq M \leq \sim 0.4$ GeV$/c^2$) by the same fitting procedure. We find that the fitted amplitude for each component, as well as the ratio of the cross sections, is proportional to the product of the projectile and target nucleon numbers, $A_P A_T$. For the four reactions, the integrated cross sections ($M \leq 0.35$ GeV$/c^2$) scale as $(A_P A_T)^\alpha$ with $\alpha = 1.06 \pm 0.01 \pm 0.02$ (syst).

A more direct comparison between the Ca + Ca and C + C data was obtained using the ratio of the cross sections as a function of the pair mass. This ratio, shown in Fig. 2, reveals two striking features. The first is that the

TABLE I. DLS dielectron data sets. "Comb" denotes the measured combinatoric background, and "Syst" refers to the uncertainty in the absolute normalization. Note the different beam kinetic energy for the ^{2}H + $^{\mathrm{nat}}$Ca data.

System	E_{beam} (A GeV)	Pair Yields e^+e^-	Comb	Net pairs	Syst
^{40}Ca + $^{\mathrm{nat}}$Ca	1.04	12 800	8102	4698 ± 145	±30%
^{12}C + $^{\mathrm{nat}}$C	1.04	4760	1919	2841 ± 82	±30%
^{4}He + $^{\mathrm{nat}}$Ca	1.04	1929	487	1442 ± 49	±30%
^{2}H + $^{\mathrm{nat}}$Ca	1.06	1828	308	1520 ± 43	±40%

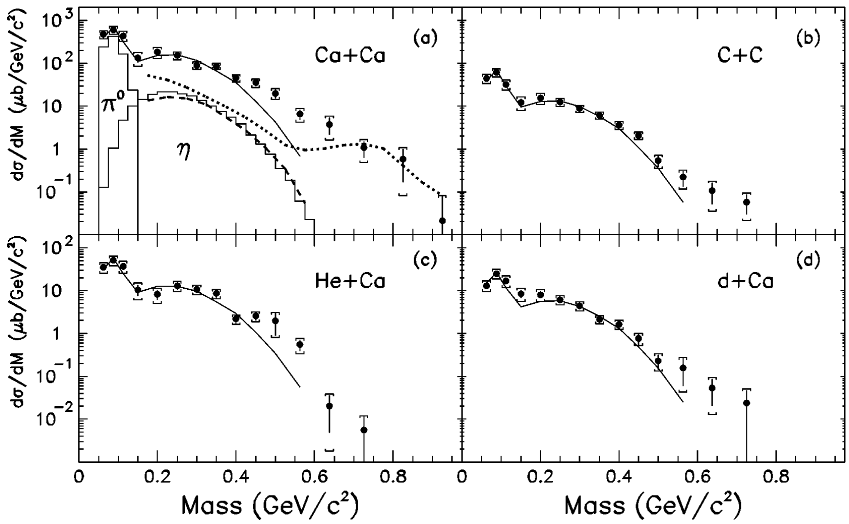

FIG. 1. The DLS measurements of the dielectron cross sections from (a) Ca + Ca, (b) C + C, (c) He + Ca, and (d) d + Ca reactions. Panel (a) also contains the calculated signal from the BUU simulations of Ref. [9] (dotted line) and histograms showing the π^0 and η decay contributions as estimated from the TAPS measurements and an isotropic thermal model. The dashed line represents the η component of the BUU calculation. The solid lines in all four panels show our fit to the low-mass data using the π^0 and η decay estimates (histograms) with adjustable normalizations.

ratio is independent of pair mass for $M \leq 0.4\ \mathrm{GeV}/c^2$. Fitting the ratio to $d\sigma/dM \propto (A_P A_T)^\alpha$ gives $\alpha = 1.01 \pm 0.03 \pm 0.04$ (syst)—indicated by the line in the figure. This value is consistent with the calculations of Ref. [7] for pairs from η decay ($\alpha = 0.87 \pm 0.1$) and Δ decay ($\alpha = 0.95 \pm 0.1$) produced in symmetric reactions ranging from Ca + Ca to Au + Au, and similar behavior has also been found for subthreshold K^+ production at 1.0 A GeV [18]. Such a large value of α is unexpected for pairs from π^0 Dalitz decays, which are expected to dominate the low mass region $M \leq 0.2\ \mathrm{GeV}/c^2$. Because of the shape of the DLS acceptance, however, the detected low mass pairs are concentrated at rapidities $\geq y_{\mathrm{beam}}$, and this may explain their strong $A_P A_T$ dependence.

The second notable feature of the CaCa/CC ratio is the increase for $M \geq 0.5\ \mathrm{GeV}/c^2$, where fitting gives $\alpha = 1.40 \pm 0.13 \pm 0.04$ (syst). The data in Fig. 1 suggest that this value of α is due to high-mass contributions to the Ca + Ca data in addition to those producing the η-like shapes seen in the other systems. Although some models have suggested that these pairs are primarily from $\pi^+\pi^-$ annihilations, Ref. [7] finds that the annihilation process should have $\alpha = 1.00 \pm 0.05$ significantly different from our observation. Calculations of density-dependent effects of the medium on the pion propagator [10] show a structure at $\sim$0.5 GeV/c^2 in the ρ mass spectrum which could be contributing these additional pairs. Note that although these additional contributions could be from a source that produces pairs only with $M \geq 0.5\ \mathrm{GeV}/c^2$, the present data do not rule out a source which contributes over a larger mass range but is visible only where other contributions (e.g., η Dalitz decay) are small.

Direct comparisons of mass spectra for other combinations of data sets are not made because at higher pair masses the rapidity distributions of the asymmetric systems are different from each other and from that of the symmetric systems. In the low-mass range these differences are not observed.

Other data relevant to meson production in nucleus-nucleus collisions come from measurements by the TAPS Collaboration of inclusive differential cross sections for π^0 and η production in ^{40}Ar + $^{\mathrm{nat}}$Ca (and other) reactions at 1.0 A GeV [19,20]. The data span only a small rapidity interval near y_{cm}. Meson production data in this limited rapidity range alone cannot be used to calculate the Dalitz-decay yields of these mesons in the DLS acceptance because of the incomplete kinematic information.

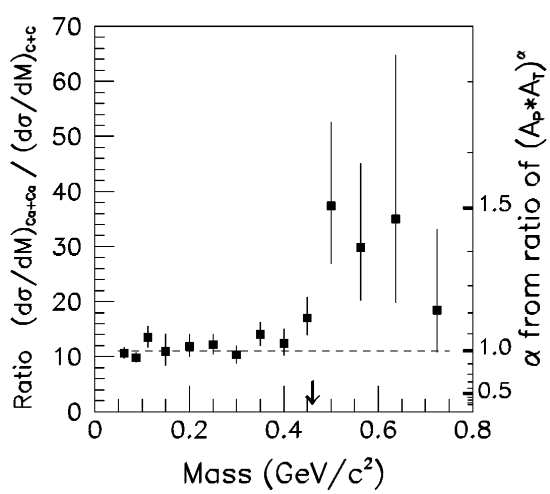

FIG. 2. The ratio of the cross sections from Ca + Ca and C + C collisions as a function of pair mass. The line on the plot is the fitted value of α from an assumed form $d\sigma/dM \propto (A_P A_T)^\alpha$. The arrow indicates the kinematic limit for pair production in NN collisions. Asymmetric errors in the ratio occur where there are large fractional errors in the denominator; they are evaluated by Monte Carlo sampling.

Thus there can be no model-independent statement regarding the fraction of the DLS pair yield that each of these mesons produces. The TAPS group calculated their total cross sections from a model where mesons were emitted isotropically from a thermal source at y_{cm}. They obtained the temperatures of these sources by fitting their measured M_t spectra. Both the magnitude and M_t dependence of these data are reproduced by the BUU model [9].

We have used the TAPS midrapidity data, inferred temperatures, and thermal model to calculate the contributions of their measurements within the DLS acceptance. This is the simple model referred to above. (We use a value of the η cross section 30% larger than the TAPS value because our data were taken at a higher beam energy [21].) The results are the histograms of Fig. 1(a). The contribution from π^0 Dalitz accounts for most of the Ca + Ca cross section below 0.15 GeV/c^2. The η Dalitz result, which is consistent with the η component of the BUU calculation [9], is approximately 10% of the DLS yield near 0.25 GeV/c^2.

Significant $(1 + a\cos^2\theta)$ anisotropy is observed in both charged pion data [22,23] and subthreshold K^+ production [18]. Because the DLS acceptance is small at y_{cm} and peaks at y_{beam}, this angular distribution for meson production gives larger Dalitz-decay yields than one which is isotropic. Our calculations show that the η yield increases more than that from the π^0. Without direct information on the angular distribution of η production we cannot quantify the size of this effect. Nevertheless, given the significant uncertainties in both data sets [24], we find that the TAPS data are not inconsistent with η Dalitz decay contributing as much as 50% of the DLS pair production in the mass range 0.2–0.4 GeV/c^2.

In conclusion, we have presented dielectron measurements from Ca + Ca, C + C, He + Ca, and d + Ca collisions at 1.0 A GeV. We have measured an order of magnitude more pairs than the original [1] DLS measurement. We find that the low mass cross section in the Ca + Ca system is significantly larger than the previous data set and model calculations that followed its publication. Also, we have made high statistics measurements of three new systems. The low-mass cross sections from these four data sets reveal a mass-independent scaling of $d\sigma/dM \propto A_P A_T$, suggesting similar dynamics for the dominant source mechanisms in reactions ranging from d + Ca to Ca + Ca. While the values of the low-mass cross sections disagree with an extrapolation of a simple model used to interpret the TAPS results, and with recent model results, we point out that the *shape* of the data can be approximated by pair distributions characteristic of π^0 and η Dalitz decays. At higher pair mass, the ratio of Ca + Ca to C + C cross sections is much larger than the $A_P A_T$ ratio, indicating that a density-dependent mechanism(s) may be exhibited in this mass region.

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[24] The dominant error from DLS is the 30% overall normalization. The dominant errors from TAPS are a 65% statistical error and a systematic error on the combinatoric subtraction that is not discussed in their paper. Since the TAPS η measurement contains a signal-to-noise ratio of about 0.1, even a 5% bias in the background could lead to a correction of 50%.