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Probing nuclear matter with dielectrons—results from the Bevalac*

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Abstract

The use of dielectrons to probe extreme conditions in nuclear matter is discussed. Earlier results from p-A and A-A studies by the Dilepton Spectrometer (DLS) collaboration at the Bevalac are briefly reviewed. Preliminary results on the yield of dielectrons in p-p and p-d interactions at 1.0 and 4.9 GeV are presented. Future directions of the DLS program, with the expectation of higher statistics, is outlined.

1. INTRODUCTION

A systematic study of dielectron (e^+e^-) production has been carried out by the DLS collaboration [1] at the Bevalac in p-A and A-A collisions [2-5]. Recently, p-p and p-d measurements have been added to complement these earlier results. As shown schematically in Figure 1, hadrons being strongly interacting particles are generally thought to reflect the surface properties of the hadronic matter produced in the collision. Whereas, dielectrons and photons, due to their relatively weak interaction with matter are viewed as good probes of the early stage of the collision process in which high temperature (50–100 MeV) and baryonic density (2–4 × normal) are expected to occur. Since quark degrees-of-freedom are not expected to play a role at Bevalac/SIS energies, sources of dielectrons are expected to result from hadronic bremsstrahlung and pionic annihilation as radiation from the hot, dense phase and various decay processes (e.g., Dalitz decay of the π^0) as background. Theoretical calculations have shown that dielectron production is sensitive to the temperature and density achieved in nucleus-nucleus collisions and may provide unique information on the dynamics of pions in hot nuclear matter [6-9].

The early phase of the DLS program focused on measuring the invariant mass (0.05–1.2 GeV) and p_t (<0.8 GeV/c) spectrum of e^+e^- pairs produced near midrapidity in p-Be collisions at 1.0–4.9 GeV (incident beam kinetic energy) and Ca-Ca collisions at 1–2 GeV/nucleon. With the addition of a multiplicity detector to provide information on centrality, Nb-Nb collisions have been studied [10]. The latest phase of the DLS program involves measurements of p-p and p-d collisions at 1.0 and 4.9 GeV to study dielectron production at the elementary nucleon-nucleon level and to provide data which may allow us to disentangle the contributions from hadronic and bremsstrahlung processes in these collisions. The DLS is a large

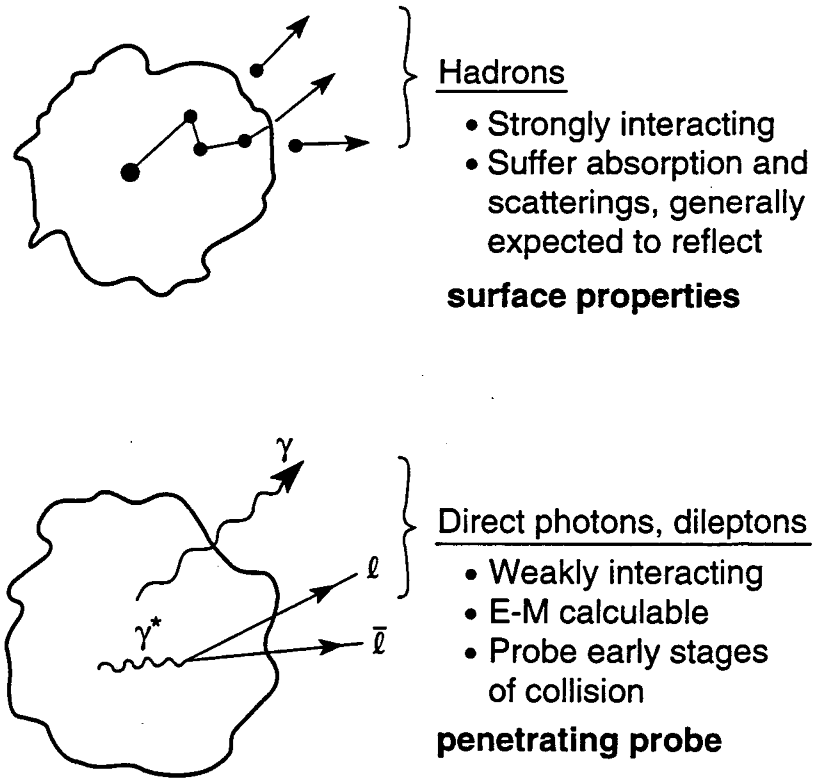

Figure 1. Probes of nuclear matter (hadronic, electromagnetic).

acceptance, twin-arm magnetic spectrometer with particle tracking and identification capability. A complete description of the DLS can be found elsewhere [11].

2. EARLY RESULTS FROM THE DLS

Initial results from the DLS were reported at the St. Malo Nucleus-Nucleus Conference [12], and it is worth reviewing the highlights of those measurements. Figure 2a shows the dielectron mass spectrum obtained in p-Be collisions at 4.9 GeV. Clear evidence for a positive signal above the estimated (dashed line) Dalitz background is seen. While a positive signal is observed at lower incident energies, the overall yield of dielectrons decreases rapidly with energy. Substantial structure is evident in the 4.9 GeV data. At higher masses, an enhancement is observed in the region of the ρ-ω mesons; while a dip-bump structure occurs in the region of 250–300 MeV, near the $2m_\pi$ threshold, possibly rising from the annihilation of pions in the nuclear medium. Additional insight into this structure may be obtained by studying the energy dependence of the integrated cross section for dielectrons with pair masses >200 MeV [3]. As seen in Figure 2b, the integrated DLS data (squares) rise rapidly to join with the two higher energy points. The dashed curve, which is a representation of the energy dependence for single pion production, is much flatter than the data, while the cross section for dipions (solid line) exhibits an energy dependence similar to the data. This observation, along with the fact that the

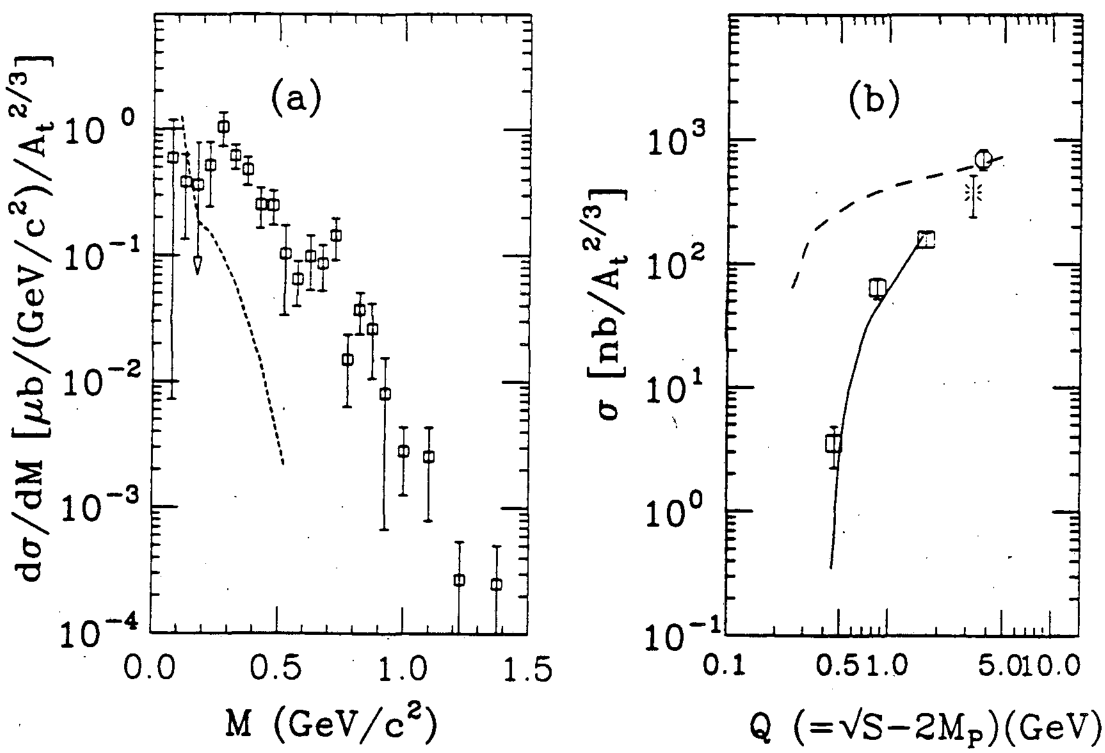

Figure 2. (a) Invariant cross section for e^+e^- production in p-Be collisions at 4.9 GeV. Dashed line shows Dalitz contribution. (b) Excitation function for same process (three lower points are from DLS). Dashed line is single pion; solid is dipion (both scaled by fine structure constant/2 squared). Note that Dalitz contribution is not subtracted.

structure occurs in the region of $2m_\pi$, has led to the speculation that pion annihilation may play a strong role in these processes. If true, this could provide new insights into the dynamics of pions in hot nuclear matter. However, it has been pointed out by Xiong et al. [13] that several processes (e.g., η-meson production) may display a strong threshold-like behavior in the 1–2 GeV incident proton energy range. Thus, a simple superposition of one or more such channels could give rise to the effect seen in Figure 2b. It is clear that considerably more experimental and theoretical work must be carried out before a definitive statement can be made concerning the source of the structure seen in the DLS data near $2m_\pi$.

Figure 3 shows the dielectron signal for 1.05 GeV/nucleon Ca-Ca collisions. A strong signal is observed for masses >200 MeV above the estimated Dalitz decay background (dashed line). These DLS results have stimulated a number of theoretical calculations [6–9,13,15] which have focused on dielectrons resulting from known hadronic processes as incorporated in thermodynamic, cascade and various transport models. These treatments generally include hadronic bremsstrahlung (dominantly p-n), radiative decay of Δ's and N*s and pion-nucleon and pion-pion annihilation contributions. It should be noted that most of these models fit only the dielectron invariant mass distribution. A stronger constraint, for any model, would be to simultaneously fit the other observables in the DLS data,

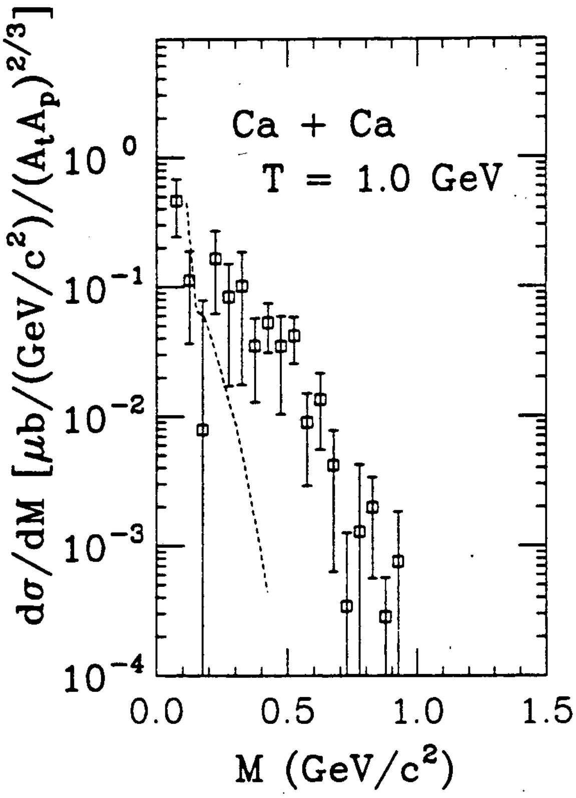

Figure 3. e^+e^- production for Ca-Ca collisions at 1 GeV/nucleon.

e.g., transverse momentum and rapidity distributions. Effects due to the production of η-mesons have generally been left out for the Ca-Ca case. However, as shown at this Conference by Professor Kienle [14], η-production has been recently measured at SIS for Ca-Ca at 1 GeV/nucleon and must be considered as a potential contributor to the dielectron spectrum in all future model calculations.

3. DIELECTRONS PRODUCED IN P-P AND P-D COLLISIONS

There are a number of reasons why studies of dielectron production in p-p and p-d interactions should be carried out. First, in order to understand the production of dielectrons in p-A and A-A collisions, it is essential to have adequate information on the elementary processes (p-p and p-n) at the same energy to determine if the observation of any effects are over and above those present at the nucleon-nucleon level. High quality data are also needed as input for model calculations of the p-A and A-A interaction leading to dielectrons. Finally, one hopes to learn about the role of hadronic bremsstrahlung through a comparison of p-p and p-d data. The various model calculations which have been carried out generally assume that the p-n term dominates the p-p term (in the framework of the soft-photon dipole approximation [6,13,15]). In addition, some calculations indicate that the bremsstrahlung term is strongly energy dependent and actually dominates the contributions from other sources when applied to the 4.9 GeV p-Be DLS data. This suggests that the ratio of dielectron production in p-p and p-d collisions should increase with energy, particularly if the bremsstrahlung term dominates other sources such as the radiative decay of the Δ and pion-pion annihilation as suggested in a number of calculations [7,13]. Based on such calculations the ratio, R = pd/pp ≅ 1 + pn/pp, should vary between about 3 at 1 GeV and increase to a value of 6 or larger at 4.9 GeV. In order to carry out this measurement, given the relatively low yield of dielectrons expected from p-p and p-d interactions, a one month dedicated run of the DLS was required. This was accomplished in the fall of 1990 and the preliminary results are indicated below.

Figure 4 shows the measured mass spectrum for p-d (top left panel) and p-p (lower left panel) interactions at 4.9 GeV. The p-d data set has about 4600 pairs, while the p-p data set has about 2900 pairs. The sum of these two data sets represents an order of magnitude increase over the statistics of the earlier p-Be study at 4.9 GeV. The high quality of these new data is evident in their spectral shapes. The top curve in the two left panels represents opposite sign pairs, while the shaded area is for like-sign pairs. The subtracted distributions, which represent the "true signal" are shown in the right-hand panels. The ρ-ω region is prominent in both distributions. Figure 5 shows the ratio, R, as described above, for the 4.9 GeV data. It is not a strong function of the invariant mass of the pair. The preliminary yield ratio, averaged over invariant mass, is found to be 1.64 ± 0.05 at 4.9 GeV and 2.0 ± 0.4 at 1.0 GeV. The larger uncertainty associated with the lower energy is due to the much smaller statistical sample (summed data set <300 pairs). A relatively weak energy dependence for the ratio is observed. Thus, these preliminary results are in striking contrast with initial expectations based on theoretical assumptions (e.g., soft photon approximation) employed in many of the calculations to date. Indeed, values of the ratio near 2 would be expected if hadronic sources were dominant over bremsstrahlung sources. This simple ratio must be better understood before conclusions can be drawn about dielectron production in p-A and A-A collisions. One possible avenue lies in the observation that the omission of particle production (implicit in the soft photon approximation) is really inconsistent with the fact that the nucleon-nucleon cross section is highly inelastic at these energies. Viewed in a slightly different way, the virtual photons responsible for the dielectrons in the final state are quite massive (0.1–1.2 GeV) leading to highly inelastic final states.

4. CENTRALITY OF DIELECTRONS IN A-A COLLISIONS

If dielectrons are to be a useful probe of the hot, dense phase of the collision process, it is essential that they be associated with central collisions. In order to determine the centrality of the collision process for the DLS nucleus-nucleus studies, a 96-element scintillation array was added in 1989. Preliminary results on the average charged particle multiplicity (at the trigger level) for the case of Nb-Nb collisions at 1.05 GeV/nucleon [10] are shown in Figure 6. The smooth curve represents the shape of the multiplicity distribution as determined by the DLS multiplicity detector for the case of a hadron-hadron trigger. This shape is reminiscent of what is expected for a minimum-bias type trigger in which low multiplicities are associated with peripheral collisions and larger ones with more

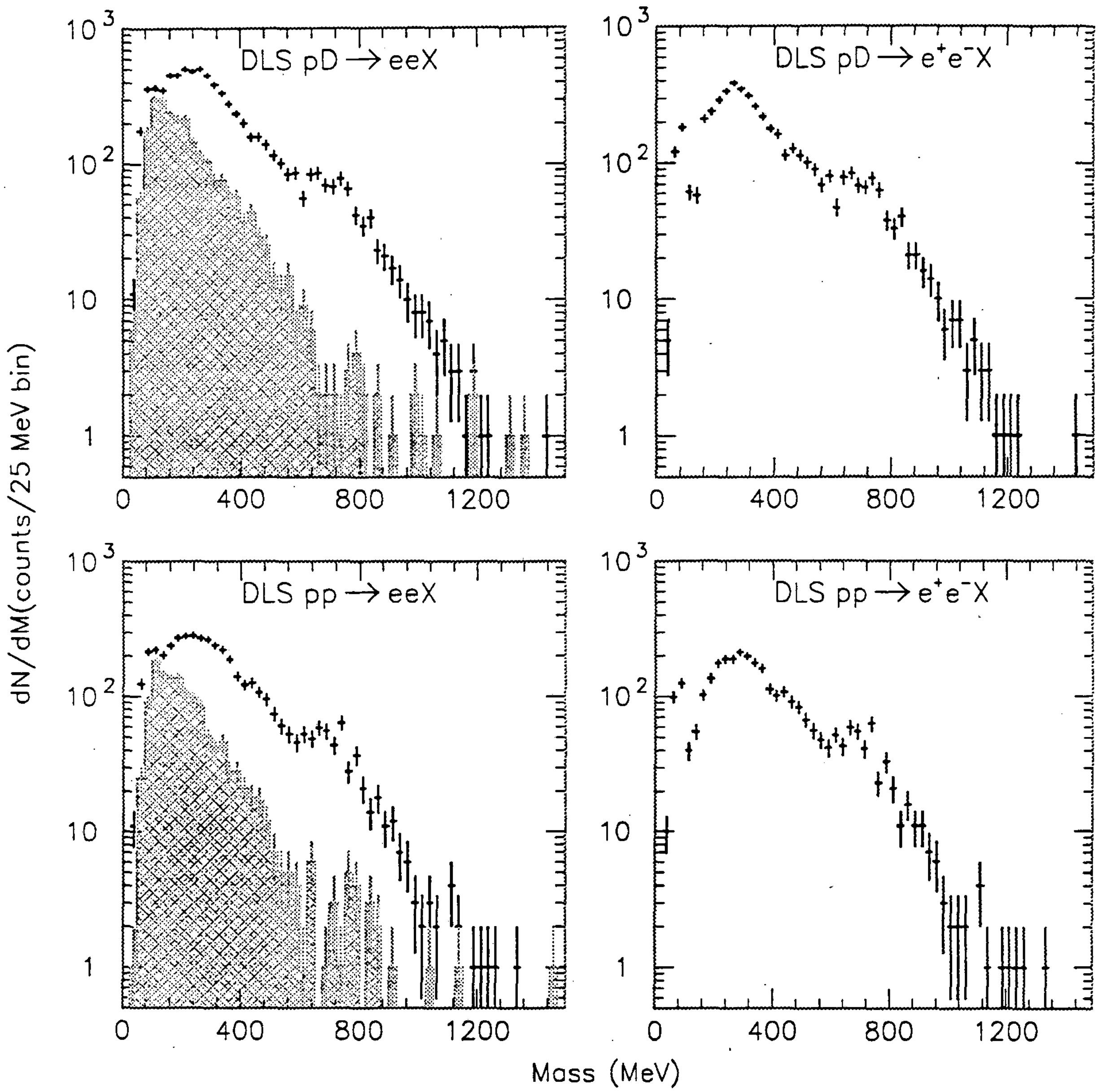

Figure 4. Preliminary results for dielectron mass spectrum from DLS for 4.9 GeV p-d (upper) and p-p (lower). Subtracted (opposite sign-same sign) distributions (right panels) are "true pairs."

central collisions. However, the histogram, which is the result of a dielectron trigger, is seen to peak at much higher values of charged particle multiplicity, consistent with events coming from central collisions. While the preliminary sample of dielectrons obtained in the Nb-Nb study is small, the associated charged particle multiplicity is consistent with these events occurring in central collision processes.

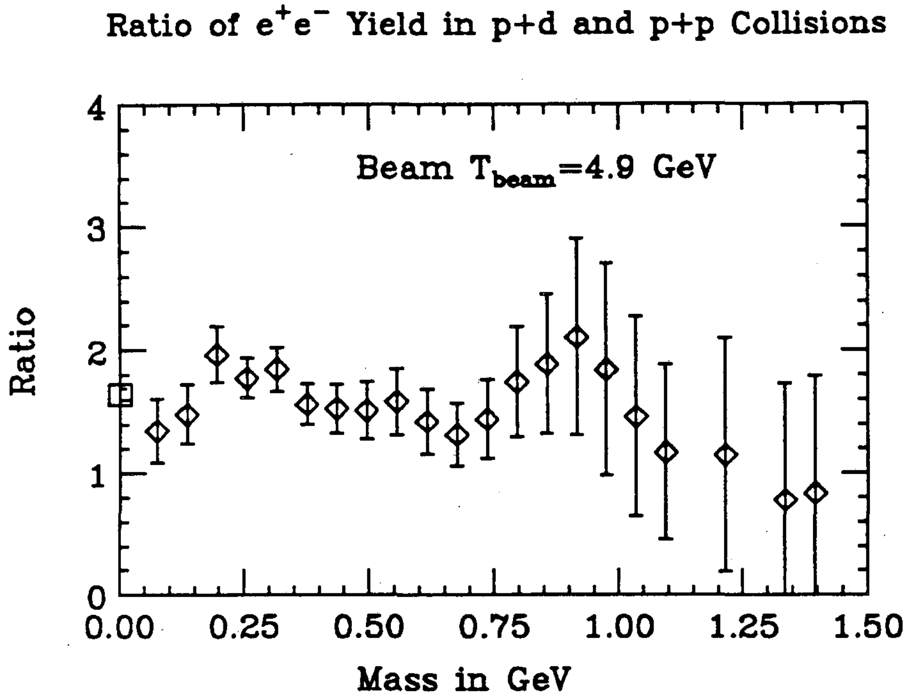

Figure 5. Preliminary value of the ratio (R = pd/pp) of the yields for e^+e^- pair production at 4.9 GeV. Average value of R indicated by square.

5. FUTURE DLS PROGRAM AND OTHER POSSIBILITIES

The future program with the DLS at the Bevalac will involve two distinct parts. The first part being completion of the liquid target (p-p and p-d) aspects of the program. Higher statistics will be acquired at 1.0 GeV and data will also be taken at 2.1 GeV for the determination of the pd/pp ratio. In order to ascertain possible contributions to the dielectron mass spectrum from the η-meson, we plan to take data near 1.6–1.7 GeV, somewhat above the threshold for η-meson production. Unless something new occurs in these data, the liquid target program should be completed in late 1991 or early 1992. The remaining phase of the DLS program will then turn to a high statistics study of dielectron production in Ca-Ca collisions at 1.05 GeV/nucleon in the period 1992–1994. During this time we expect to improve, by an order of magnitude, our previous data sample at this energy. Particular attention will be given to the higher mass region where pion annihilation may play a prominent role. In addition, with the capability of multiplicity selection, the data can be studied as a function of the centrality of the collision. Wolf et al. [15] have suggested that the contributions from pion annihilation and hadronic bremsstrahlung are sensitive to impact parameter. Multiplicity selection of the data may provide a means of adjusting the relative strengths of these contributions.

The existence of the early DLS data and the many theoretical calculations that have resulted have encouraged others to look at dielectron production as a means of probing hot, dense hadronic matter, at energies up to several GeV/nucleon. Workshops have been conducted in Europe towards a potential program at SIS.

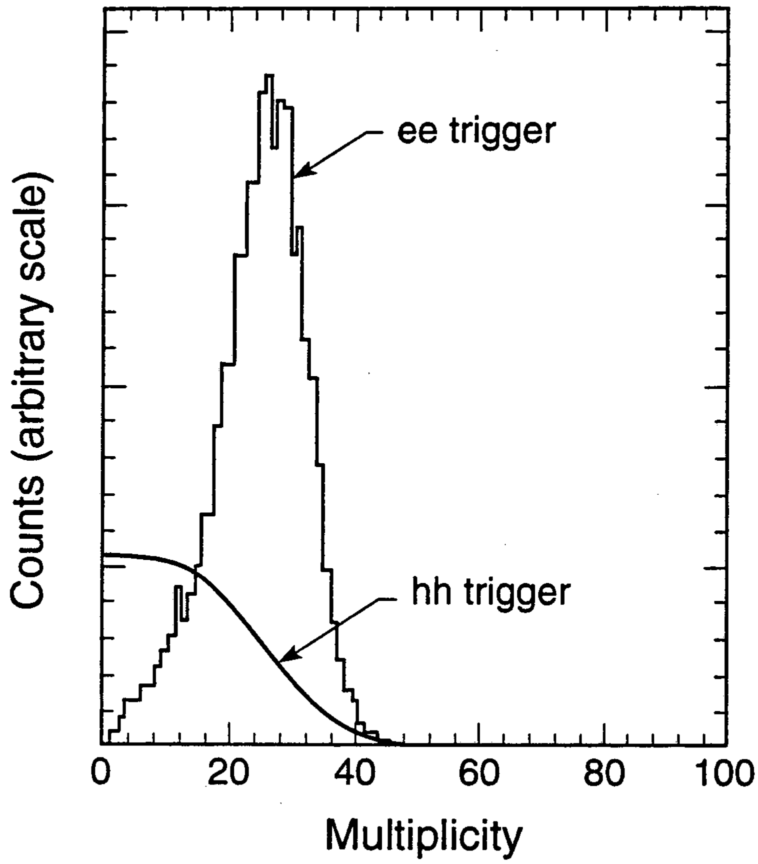

Figure 6. Associated charged particle multiplicity distribution for Nb-Nb collisions at 1.05 GeV/nucleon for two different trigger conditions (hh = dihadron; ee = dielectron).

Machine capabilities exist at several laboratories, worldwide. At Saclay, the availability of large amounts of beamtime for protons in the 1–3 GeV range could be used for a program concentrating on higher statistics for p-p, p-d, and perhaps p-light nucleus studies. As mentioned above, the new heavy ion capability of SIS provides the potential for creating a new detector system to go beyond the Ca-Ca measurements of the DLS. Finally, at higher energies, we have heard at this conference of a possible heavy ion option with 5 GeV/nucleon Ca beams at KEK. This would represent a good opportunity to go beyond the DLS program at higher energy.

In summary, the data from the DLS collaboration and the theoretical calculations carried out to explain these data have provided a first glimpse into using dielectrons to study the hot, dense phase of hadronic matter at incident energies of a few GeV/nucleon. Over the next several years, the DLS will carry out experiments aimed at substantially enhanced statistics with the addition of selection on associated charged particle multiplicity for isolating central collisions. Future programs at other laboratories could build on these results and would be able to study dielectron production with the heaviest nuclei. Success for any program involved in rare particle measurements, such as dielectrons, will require substantial dedication of machine time on a regular basis. These experiments should build into their basic design the ability to measure many of the backgrounds, such as π^0 and η Dalitz decays, so that the remaining spectra are as sensitive as possible to the production and decay of hot hadronic matter.

FOOTNOTE AND REFERENCES

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