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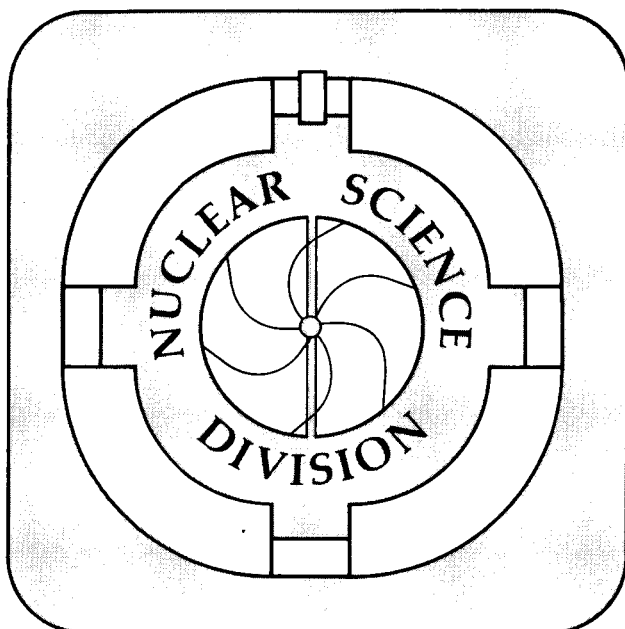
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MEASUREMENTS OF e^+e^- PAIR PRODUCTION AT THE BEVALAC

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INTRODUCTION

It has come to be generally recognized that a relativistic nuclear collision (RNC) can only be described as a complex dynamic evolution of the not-so-many-body system, whether the components of the system are taken at the hadronic level or at the quark level. The evolution proceeds from an initial state of two separated nuclei, through stages of: first nucleon-nucleon collisions; increasing rates of collisions and particle production (heating and compression); gradually decreasing rates of collision and particle production rates (cooling and expansion); and, finally, decoupling of various particle types from the overall system (freeze out). (Parentheses enclose the adiabatic thermodynamic terms that may in some circumstances be relevant descriptions for parts of this process.) It is, in particular, the operation of the dynamics during the stages of high excitation energy and high particle density that are of interest in studying such collisions. Unfortunately we cannot build a detector that will produce information about a particular part of this process. Our detectors integrate over the entire space-time history of a collision - only the dynamics itself determines how the final-state phase space will be populated with particles.

If the detected particles are hadrons, then the dynamics of the strong interaction makes it probable that the last interaction occurred late in the history of the collision and in the outer parts of the system. To infer the state that the system had earlier in its history from information that is mostly about its latest stages requires that one understand the dynamics. (But then one would not need the experiments!) While a complete theory accounting for particle production, scattering, absorption and escape must be consistent with the final-state hadronic observables, the necessity to understand all stages of the evolution in order to study the most interesting parts make this a daunting task.

A desirable probe should not be subject to multiple interactions within the nuclear medium (therefore not a hadron) but must have a detectable yield, which eliminates particles with only weak interactions. Thus only the electromagnetic interaction remains, and one must consider real photons and charged leptons. Detection of single real photons is difficult because of the large yields from $\pi^0 \rightarrow \gamma\gamma$, and it is not possible to arrange that an external lepton scatter from the system at a relevant space-time point during the collision. The only remaining candidate is the virtual photon, which decays into a lepton pair. The masses and momenta of the virtual photons will be of the same magnitude as the excitation energies and the momenta associated with bulk motion, which are thought to be in the range of a few hundred MeV. For fixed target experiments with beam energies $T_{\text{beam}} < 15$ A GeV, it

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Figure 1. Diagrams for annihilation and bremsstrahlung.

is easier to measure (with adequate kinematic resolution) electron pairs than muon pairs. Thus there are strong arguments that fix the choice of the relevant probe for nuclear collisions in this energy range. The yield of lepton pairs is, however, even lower than that of real photons because of the extra electromagnetic vertex; the experimental requirements that result from this will be discussed below.

There are only two diagrams which describe the mechanisms that produce lepton pairs - annihilation and bremsstrahlung (Fig. 1). If the parent particles are point-like (quarks or leptons), then QED gives a complete description of the cross sections. In a Fermi gas of such particles, the yield of electron pairs increases rapidly with temperature and density (ie, energy and frequency of the interactions). (The increased yield that occurs during the interesting stages of the collision will be offset somewhat by the larger space-time extent of the later stages, but the kinematic information conveyed from these two regions will be quite different.) If the parents of the virtual photon are hadrons, then the vertex coupling the hadrons to the virtual photon must be described by a form-factor that accounts for the complexity of the underlying QCD structure. Thus, to evaluate electron pair production in nuclear collisions, one first needs to understand (or be able to parametrize) the 'elementary' production by free hadrons.

A complete kinematic description of a lepton pair (virtual photon) requires 6 independent variables, (eg, the 3-momenta of the two particles, the masses being fixed) in contrast to the case of a real photon, where there are only 3 independent variables. The mass and momentum of the virtual photon may be specified independently, with the remaining variables being the two angles specifying its production direction, and the two angles of the decay in its rest frame. It has become customary (at least for data taken at high incident energies) to use as kinematic variables: the mass, M ; the transverse momentum, P_T ; and a longitudinal variable, either the rapidity - Y , or the scaling variable - X . Data are almost always presented as a function of only one of these variables. This may be due to the difficulty inherent in presenting multi-dimensional data, to poor statistics, to limited experimental acceptance, or to some combination of these reasons. It should be noted, however, that these one-dimensional projections always represent integrations over the remaining variables - integrations within which the shape and limits of the acceptance of the experimental apparatus must be taken into account. The effects of the acceptance must be understood in comparing experimental data either to theory or to results from experiments with different coverage of the total phase space. (Comparisons of differing regions of phase space can be made *only* with the aid of a theory or model.)

Although we have a strong interest in studying nucleus-nucleus collisions using this tool (some first steps in this direction will be discussed later), most of the discussion presented here will be about our measurements in p+Be collisions. It was necessary for us to make these measurements because, in the relevant range of incident energies, the yield of electron pairs from nucleon-nucleon collisions had not been measured, nor was the hadronic production mechanism understood. A brief discussion of lepton production in hadronic collisions will help put our results in a proper framework.

I begin by defining the leptons which have *not* been of interest in discussions of previous data - ie, those which arise from the decay of a known hadron. Thus, leptons produced in Dalitz decays of π^0 's (η 's, etc), or in two-body decays of vector mesons, or in semi-leptonic decays, etc, are not the object of discussion here. (Nor, of course, are the leptons arising from photon conversion in material of the target or detectors.) The leptons which remain after these sources have been excluded or subtracted are referred to as 'direct' (ie non-decay) leptons. While they may be produced in a direct process such as bremsstrahlung, they may also come from decays of yet-undiscovered resonances. Direct production

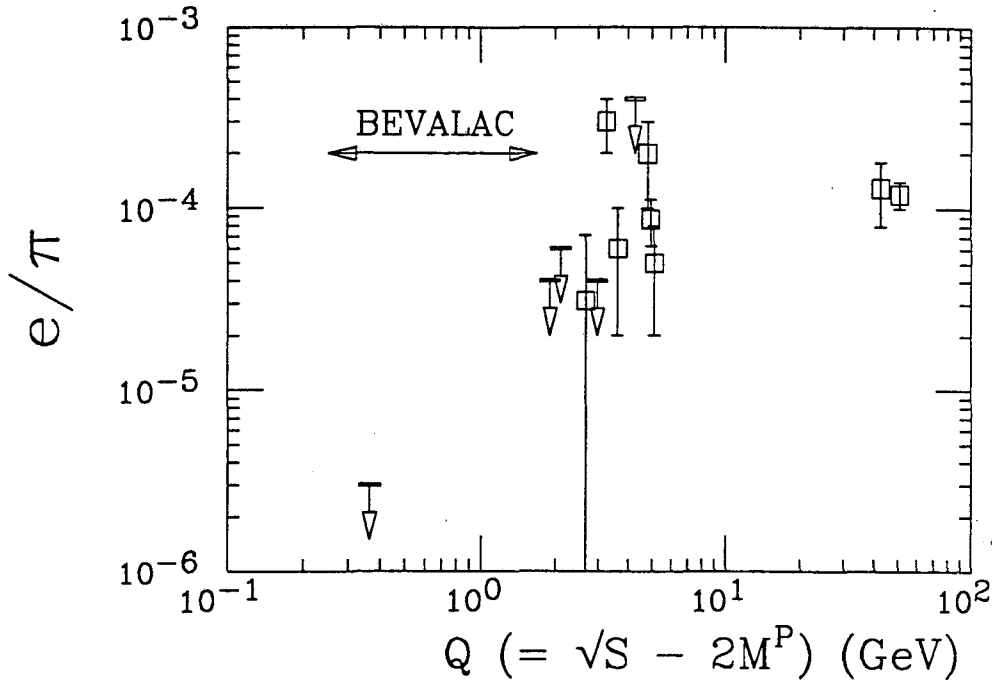


Figure 2. Energy dependence of (e/π) ratio, showing possible threshold behavior.

has been observed in measurements of inclusive production of 'single' leptons at energies of $[2.3 < Q (= \sqrt{s} - 2M_p) < 51]$ GeV.¹ ('Single' electron - one that is not a member of a 'low-mass' pair - the mass limit varies between experiments - electrons from 'high-mass' pairs are not excluded from these data.) In this energy range, and for $P_t > 1$ GeV/c, the ratio of the cross section $(d^2\sigma/dP_t dY)_{Y^*=0}$ for direct electron production to that for pion production (frequently called simply the ' e/π ' ratio) is found to be approximately 10^{-4} . A measurement of this ratio at $Q = 0.36$, on the other hand, found an upper limit of 3×10^{-6} , raising the question of a threshold in the production process.² This data is summarized in Figure 2, which also indicates the range over which the LBL Bevalac can provide data.

Measurements of lepton-pair production offer information supplementary to that obtained from the yield of 'singles'. Figure 3a illustrates the typical features observed in high-statistics, high-energy experiments. Peaks from the two-body decays of the vector mesons stand above a continuum, which at large masses is well described by the Drell-Yan model.³ (In this model the virtual photon is produced in the annihilation of a quark from one hadron with an anti-quark from the other. The approximation of asymptotic freedom used to permit the calculation of cross sections is expected to limit the validity to pair masses above 3-4 GeV. The extrapolation to lower masses thus reflects only what might be expected if the quarks within the hadrons always behaved as if they were unconfined.) At lower masses, the part of the continuum that is not produced by the kinds of decays mentioned above (ie the 'direct' part), has been referred to as "anomalous low-mass pairs", indicating that it has not been possible to account for this yield on the basis of known sources. For example, calculations of hadronic bremsstrahlung fail to account for these pairs.⁴ Calculations of the yield from annihilation of partons⁵ or virtual mesons⁶ that are produced in the collisions reproduce some features of the existing data, but because of poor statistics, no strong tests of these theories has yet been possible.

Figure 3b shows an example of the data available for the production of electron pairs, in this instance from p+Be collisions at 12 GeV.⁷ Several typical features are apparent: the poorer statistics of the electron sample; the calculated subtraction necessary to remove the contribution of the η and ω Dalitz decays (dot-dash curve); and the dashed curve due to the phenomenological model of Kinoshita, Satz and Schildknecht (KSS).⁸ The KSS model, which pieces together ad hoc assumptions about the E_t and mass dependences with an overall phase space factor to account for energy conservation, gives a good representation of the existing data. Reviews of lepton production in hadron collisions may be found in Mikamo⁹

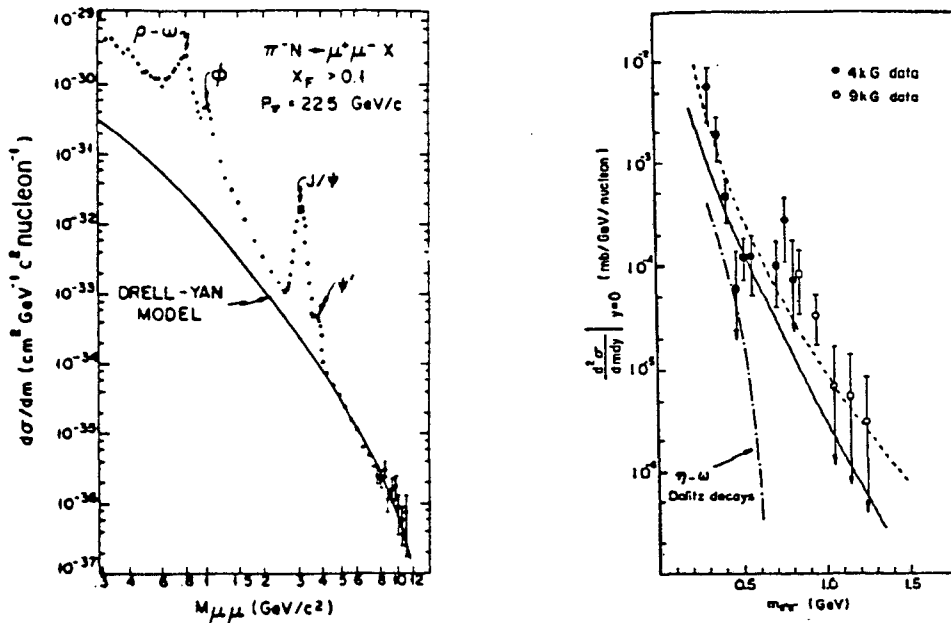


Figure 3. Mass spectrum of a) muon pairs from the Chicago-Princeton collaboration, and b) electron pairs produced in 12 GeV p+Be collisions (Ref. 7).

and Stroynowski¹⁰.

DLS DATA

The DLS (Di-Lepton Spectrometer)¹³ was designed to carry out a program of measuring electron-pair production in both p+Be and nucleus-nucleus collisions. It consists of two arms (each mirror-symmetric around its central axis) positioned symmetrically about the beam axis. Within each arm are a large aperture dipole, two scintillator hodoscopes, two one-atmosphere Cherenkov arrays, and three drift chamber stacks. The solid angle of each arm is about 200 msr. The granularity of each detector element was chosen to be adequate for the multiplicities expected in 2.1 A GeV Ca+Ca collisions. The data shown here were obtained during three running periods: December, 1986; May 1987; and January, 1988. These and other data are included in a number of papers from the DLS collaboration¹⁴, and the reader is referred to these for more detail.

The pair statistics from p+Be collision accumulated during this time are shown in Table 1. The DLS data sample was accumulated with significantly less running time than any of the three preceding experiments; the increased sample size is due entirely to the large acceptance of the spectrometer. The '# Unlike-sign', '# Like-sign' columns of this table refer to the necessity of removing the predominant background to these measurements - events in which an e+ and an e- are detected, as members of an electron pair, but which came from

Table 1. Existing low mass electron-pair data.

Source	Reaction	# Unlike-sign	# Like-sign	# True
Adams ¹¹	17 GeV π +p			165
Blockus ¹²	16 GeV π +p			107
Mikamo ⁷	12 GeV p+Be			144
DLS	4.9 GeV p+Be	732	201	531±31
	2.1 GeV p+Be	567	148	419±27
	1.05 GeV p+Be	263	111	152±19

different parents. Since essentially all electrons in the interesting energy range arise as pairs (ie, the weak decay contribution is negligible), this happens when one detects the electron (but not the positron) from pair A, and the positron (but not the electron) from pair B. (Events containing more than two detected electrons, about 1% of the final data, are discarded.) The inherent charge symmetry of this background and a charge-symmetrized operation of the spectrometer (equal amount of beam on target for each of the 4 possible magnet polarities) permits us to calculate the number of 'true pairs' (those which came from a single virtual photon) by subtracting the like-sign ('false') pairs from the opposite-sign pairs. Some fraction of the remaining 'true pairs' will be from sources that are of no particular interest in themselves (eg, high-mass Dalitz decays of known hadrons). These contributions must be calculated from known cross sections, branching ratios, form factors, etc. The contributions from the two-body decays of the vector mesons, which in themselves may be of considerable interest in nucleus-nucleus collisions, are readily identifiable as peaks in the mass spectrum.

Before turning to discussion of the differential cross sections, it is worth noting that while the fully-differential cross section is five dimensional, the graphically presented cross sections represent projections onto one dimension, and therefore have been integrated over four kinematic variables. If the cross section extends into regions that are not covered by the acceptance of the experiment then the result of integrating the (correctly) measured cross sections will not necessarily resemble the result of integrating the real cross section over the full kinematic range.

Figure 4 shows the DLS data from p+Be collisions at 4.9 GeV, projected onto the pair-mass variable. (All data to be shown have been normalized by $(A_p A_t)^{2/3}$ to give an effective nucleon-nucleon cross section.)¹⁰ The solid curve represents a calculation of the yield of pairs from Dalitz decays. For masses above 200 MeV, this contribution is always less than 10% of the measured yield. Thus there is indeed a direct, continuum signal at 4.9 GeV. In this data one observes a structure at the ρ mass, and, for masses above 300 MeV, good agreement in shape with the dashed curve which is a fit of the KSS model⁸ to the KEK data at 12 GeV.⁷ A smaller yield is to be expected at our lower incident energy. The turnover of the cross section for masses below about 275 MeV, however, is a completely

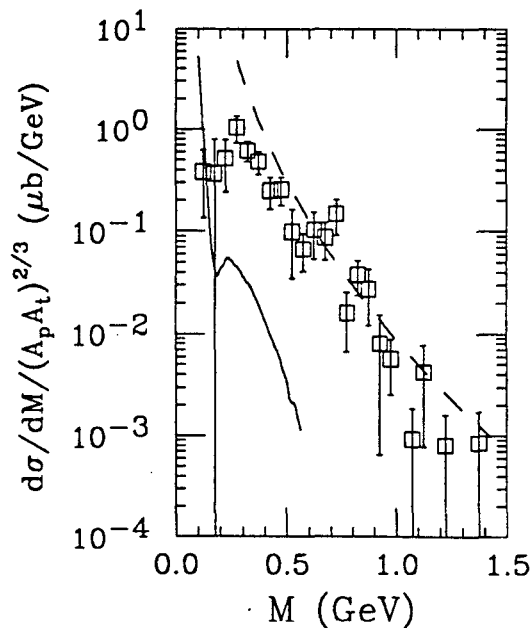


Figure 4. DLS data. Projected mass spectrum for 4.9 GeV p+Be collisions. Dashed curve fitted through KEK data at 12 GeV⁷. Solid curve - calculation of Dalitz background.

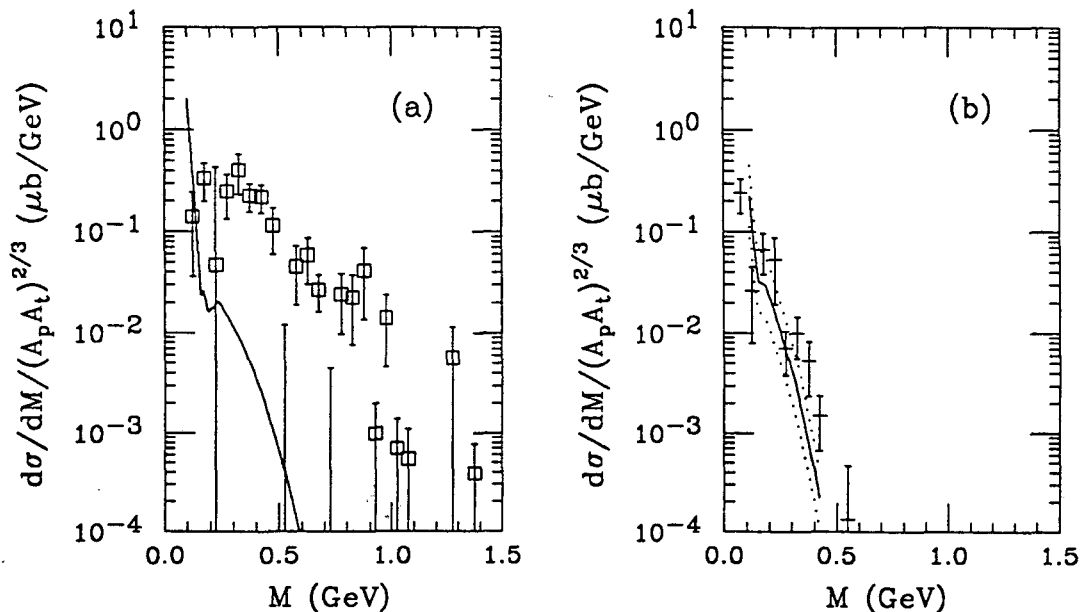


Figure 5. DLS p+Be data. Projected mass spectra at a) 2.1 GeV, and b) 1.05 GeV. Solid curve - calculation of Dalitz background.

unexpected feature, although it is not in disagreement with earlier measurements, which either have little data in this mass range, or are limited by a nearby threshold (in the case of mu-pair measurements). Although the appearance of the structure is enhanced by subtraction of the calculated Dalitz contribution, we report only the measured cross sections because the Dalitz calculation has uncertainties that are not related to this experiment. The width of this feature is somewhat larger than the experimental resolution; the significance of the structure will be discussed later.

Figure 5a shows the p+Be data at 2.1 GeV incident energy. The measured yield is well above that calculated for Dalitz decays, thus a direct continuum yield exists at this energy as well. No ρ signal is seen, which is to be expected since the available energy in the nucleon-nucleon center of mass is only 100 MeV above the ρ mass. There is also some evidence in this spectrum of a turnover of the cross section near 275 MeV, although the statistics are somewhat poorer here. Figure 5b shows the p+Be data at 1.04 GeV. Not only has the character of the spectrum changed (a much more rapid decrease with increasing mass) but the calculated Dalitz contribution now represents a larger fraction of the measured yield. The curves in the figure indicate an uncertainty of a factor of two in the cross sections on which the Dalitz calculation is based. The size of any direct continuum signal at this energy is therefore quite uncertain.

At the two higher energies, the P_t^2 dependence of the cross section is similar to that observed at energies above 10 GeV. At 1.04 GeV both the statistics and the P_t range are too limited to permit any conclusion.

I now return to a discussion of the significance of the apparent turnover in the 4.9 and 2.1 GeV cross sections for masses below about 275 MeV. To quantify the statistical significance of the turnover one must calculate the effects of the experimental acceptance upon some 'structureless' cross section and compare this to the measurements. To account for the effects of the dependence of the acceptance on variables other than mass, a usable model must give a complete kinematic description of the cross section. While the evaluation of the acceptance is straightforward, the choice of an appropriate model for the cross section is not. We have found that parameterizations of presently available models are not sufficiently constrained; they do not allow us to give a meaningful value to the statistical significance of the turnover. The question of the agreement between models and all existing

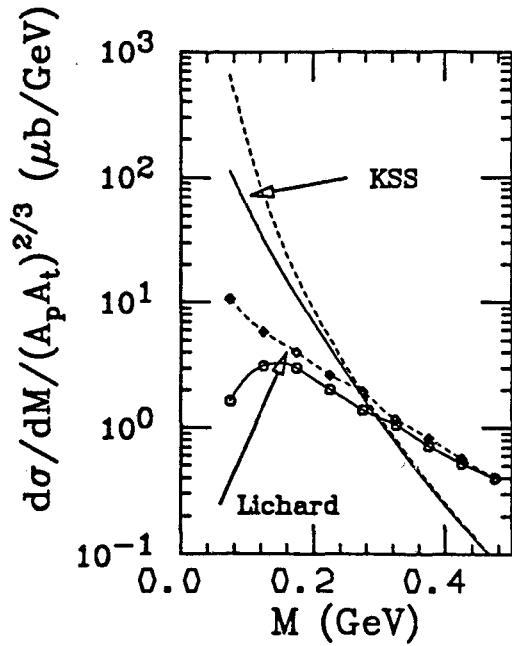


Figure 6. Projected mass spectrum calculated from Ref. 15, and from the KSS model (Ref. 8) with parameters of Ref. 7. Solid curves show effect of including effect of DLS acceptance.

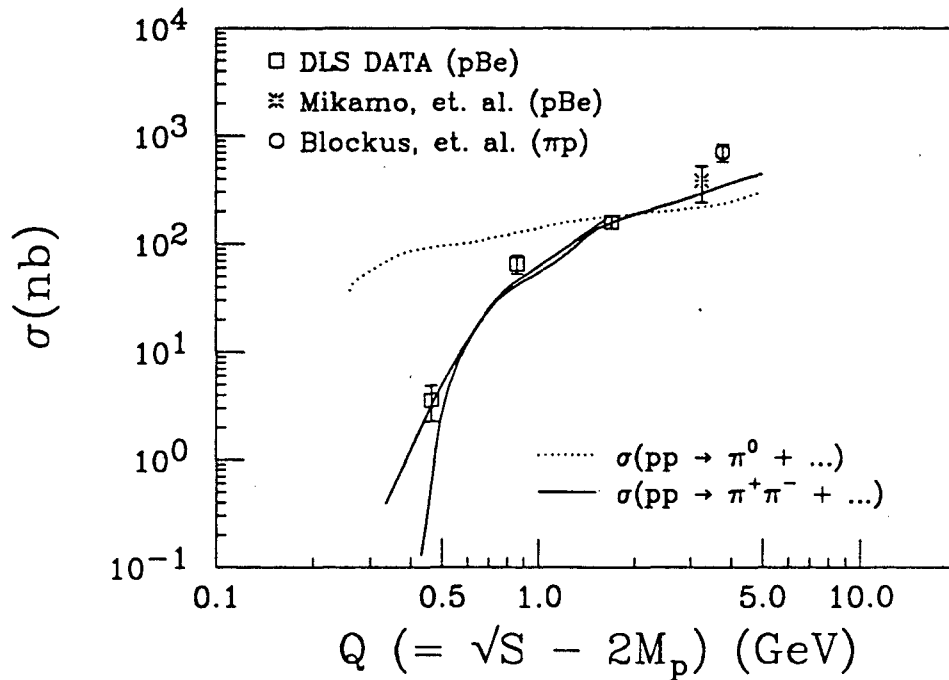


Figure 7. Integrated cross section vs. available energy in nucleon-nucleon center of mass. Curves show total cross section for inclusive production of: single pions (dots); and pion pairs (solid). Pion cross sections have been normalized to the DLS data point at $Q \approx 2$ (ie divided by about $\alpha^2/3$).

data needs to be addressed on a wider scale. We can show (Fig. 6) that for two models (that of Ref 15, and that of Ref 8 with parameters from Ref 7), the experimental acceptance has little effect on the shape of the mass spectrum for $M > 150$ MeV.

Figure 7 shows the integrated cross sections for the DLS measurements as well as those of Blockus, et al.¹⁰, and Mikamo, et al.⁷. Also shown for comparison are two curves representing the energy dependences of the cross sections for inclusive production of single pions and pion pairs. Note that the integrated cross section shows a sharp drop near the threshold for two-pion production and does not follow the rather flat production of single pions down to lower energies. This behavior and the structure observed at twice the pion suggest that, in this energy range, the production of electron pairs may be mostly due to annihilation of pairs of real pions.

To summarize our findings from the p+Be measurements:

- We find clear evidence for a direct continuum signal at both 4.9 and 2.1 GeV.
- The evidence for a direct continuum signal at 1.04 GeV is less convincing.
- The integrated cross section parallels the total cross section for inclusive production of pion pairs with a magnitude reduced by about $(\alpha^2/4)$.
- At energies where two-pion production is well above threshold, the mass spectrum of electron-pairs shows previously unobserved structure near $2m_\pi$. Other than this structure, the mass and P_t dependences, as well as the cross section for ρ production, are consistent with expectations based on data from higher energies.

The existence of the electron-pair signal at these energies makes possible the use of pairs as a probe in the study of A+A collisions at the Bevalac and SIS; the suggestion that this yield may be from annihilation of pions makes this possibility exciting. These data also demonstrate some of the advantages of using a detector with large acceptance for this type of measurement.

As stated earlier, some first steps have been made toward making measurements for A+A collisions. The pair statistics obtained from our first Ca+Ca runs are given in Table 2. The effects of the increased pion multiplicity on the relative magnitude of the like-sign pair background and the consequently larger statistical error in the subtracted data are apparent in these numbers. Figure 8 shows the Ca+Ca data sets, and Figure 9 compares the 1.0 GeV data for p+Be and Ca+Ca. For both the 1.0 and 2.0 A GeV Ca+Ca data the general features of both the mass spectrum and the (not shown) P_t dependence are similar to those obtained in p+Be collisions above 2 GeV. For example, the measured true pair yield from Ca+Ca lies well above the calculated Dalitz contribution at 1.0 GeV as well as at 2.0 GeV, which was not true for p+Be. Furthermore, even with the limited statistics, one can see that for the 1.0 GeV data the average pair-mass is higher for Ca+Ca than for p+Be. An exponential fit to the spectra (for $M > 200$ MeV) gives inverse slopes of 125 ± 16 MeV for Ca+Ca and 71 ± 18 for p+Be. A calculation shows that there is only a small increase in average available center-of-mass energy due to internal nuclear motion (Fermi momentum), and thus does not offer a ready explanation for the observation. Pion annihilation, on the other hand, is an interesting, if speculative, possibility. While two-pion production is suppressed at this energy, the multiplicity (and density) of pions produced singly in independent nucleon-nucleon collisions may be high enough in Ca+Ca collisions so that the annihilation mechanism can account for the increased yield at higher masses. If this hypothesis were correct higher statistics would show a ρ peak not seen in p+Be or in nuclear collisions with very small A. We find that, for total yield at 1.0 A GeV, the ratio of Ca+Ca to p+Be shows a dependence $(A_p A_t)^{1.0 \pm 0.1}$. (Note that this is in disagreement with the $(A_p A_t)^{2/3}$ scaling that we have used in reporting effective nucleon-nucleon cross sections from the measured data.)

Table 2. DLS Pair Statistics for Ca+Ca data

T (A GeV)	# Unlike-Sign	# Like-Sign	# True
2.0	94	45	49±12
1.0	731	476	255±35

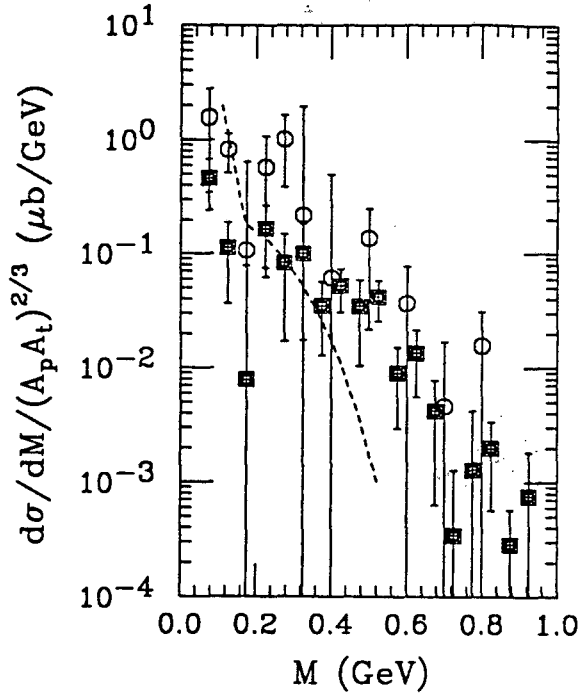


Figure 8. DLS data. Projected mass spectra for Ca+Ca collisions at: 2.0 A GeV (circles); and 1.0 A GeV (solid). Dashed lines are calculated Dalitz yields.

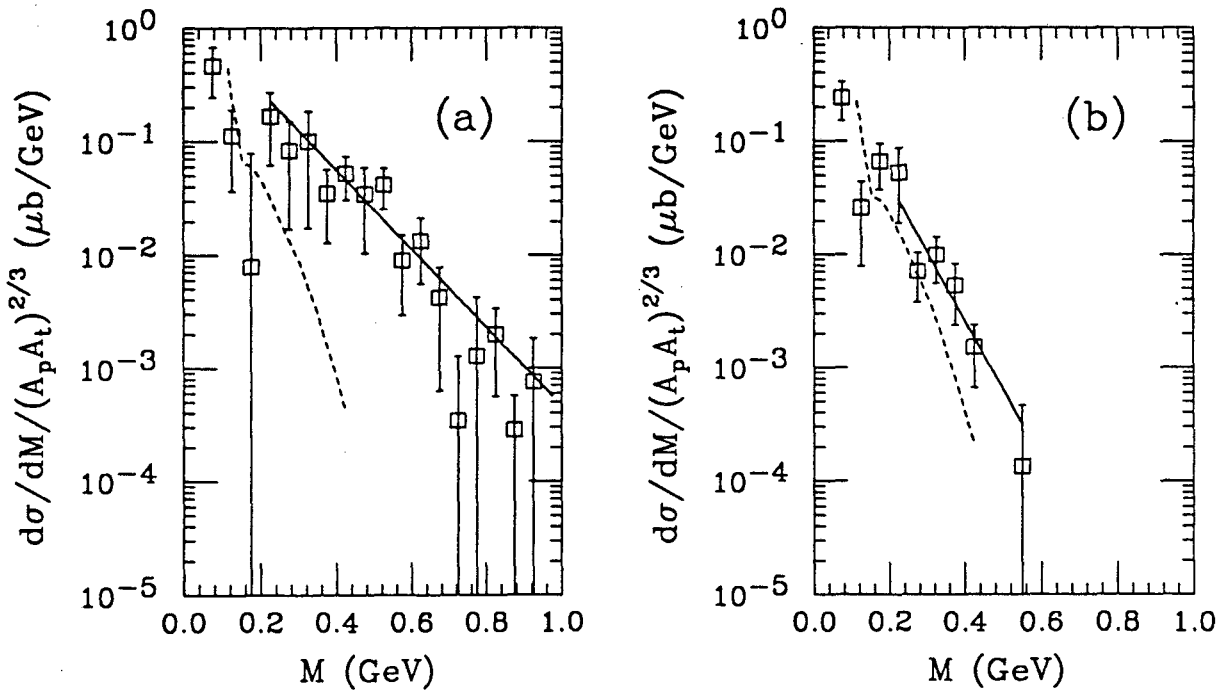


Figure 9. DLS data. Projected mass spectra at 1.0 A GeV for collisions of Ca+Ca (a), and p+Be (b). Solid lines are fitted exponentials, and dashed lines are calculated Dalitz yields.

These first data show the possibility of experiments using e^+e^- pairs as a probe of nuclear collisions at beam energies for which the full mass range is presently available. Much better statistics will be required to permit detailed study of the collision process.

Because of the importance of making comparisons between theory and experiment using the full dependence of the yield on all kinematic variables, and because of the necessity to account for the experimental acceptance in making these comparisons, we will make both published data and the experimental acceptance available to interested parties in computer readable form. At present the data and acceptance are kept in a three dimensional table with variables (M, P_t , Y).

FUTURE

In 1989 we will begin a series of measurements on p+p and p+d collisions to differentiate between hadronic and nuclear effects, and to try to extract the contribution from bremsstrahlung. Heavy ion running during this period will be devoted to acquiring a high-statistics data set for Ca+Ca (with associated multiplicity), and to pushing the system toward higher projectile/target masses. While the present system is well suited to measurements of p+N, p+A and 'light' nuclear systems, in 1990 and beyond it may be possible to make measurements for still heavier beam-target combinations and to improve the achievable statistical precision by further improvements to the instrumentation - eg, the replacement of one or more of the existing segmented Cherenkovs by RICH (Ring-Imaging Cherenkov) detectors.

In its first two years of operation the DLS has demonstrated the existence of useful yields of electron pairs for incident energies down to 2 GeV in the case of p+Be, and down to 1.0 A GeV for Ca+Ca, and it has also demonstrated both the feasibility and the advantages of using a device with large solid angle. For the long term future of studies of relativistic nuclear collisions, it may be the latter fact that is the more important. There are quite general, fundamental arguments that the sensitivity of lepton pairs to the evolution of the system formed during a nuclear collision is qualitatively different from that of any hadronic probe. To me, the same arguments (and recent experimental experience) suggest that electron pairs can be made to produce information about nuclear collisions that is, in some sense, more useful than that from hadrons - a point of view that others may question. Even on the simple ground of qualitative difference, however, I propose that detectors for lepton pairs deserve parity of support with the hadronic detector programs. Large support is required - not only in funding, but in effort from theorists, and from experimenters who are willing to join existing groups or to form new ones - because it is not easy to build a detector that will produce this 'more useful' information. While the DLS represents a large increase in acceptance, an even larger acceptance is required - probably around 2π sr. A useful detector must be capable of carrying out a systematic study, varying beam energy and projectile/target masses, within a reasonable time span. At each of these settings it must produce a data sample large enough to permit full use of the dependence of the yield on the six kinematic variables. It must also be granular enough to accommodate the multiplicities associated with the most massive projectile/target combinations, and it must be clever enough to suppress the combinatoric backgrounds from low mass pairs. Schemes for constructing such detectors exist: A proposal by a Heidelberg-Weizmann collaboration to build a detector meeting many of these goals has been accepted by CERN. A proposal for such a detector at the AGS was turned down on grounds of 'too little physics/dollar'; both numerator and denominator are being worked on. Both SIS and the Bevalac could use such a detector. The primary limitation is manpower, those of working enthusiastically in this field are actively seeking discussions, advice, calculations, techniques, and collaborators.

REFERENCES

1. A. Maki et al., Phys. Lett. 106B:423 (1981), and references therein.
2. A. Browman et al., Phys. Rev. Lett. 37:246 (1976)
3. S. D. Drell and T. Yan, Phys. Rev. Lett. 25: 316 (1970)
4. R. Rueckl, Phys. Lett. 64B: 39 (1976); N.S. Craigie and H.N. Thompson, Nucl. Phys. B141:121 (1978)
5. B.J. Bjorken and H. Weisberg, Phys. Rev. D 13:1405 (1976); V. Cerny, et al., Phys. Rev. D 24:652 (1981)
6. T. Goldman, M. Duong-Van, and R. Blanckenbeckler, Phys. Rev. D20:619 (1979)
7. S. Mikamo, et al., Phys. Lett. 106B:428 (1981)
8. K. Kinoshita, H. Satz, and D. Schildknecht, Phys. Rev. D 17:1834 (1978)
9. S. Mikamo, in Tokyo INS Symposium 1979, 362 (also KEK-Preprint-79-27)
10. R. Stroynowski, Phys. Rept 71:1 (1981)
11. D. Blockus, et al., Nucl Phys. B201:205 (1977)
12. M.R. Adams, et al., Phys. Rev. D 27:1977 (1983)
13. The collaboration which has done the work presented here: J. Bystricky, J. Carroll, J. Gordon, T. Hallman, G. Igo, P. Kirk, G. Krebs, E. Lallier, G. Landaud, A. Letessier-Selvon, L. Madansky, H. Matis, D. Miller, C. Naudet, G. Roche, L. Schroeder, P. Seidl, Z.F. Wang, R. Welsh, and A. Yegneswaran
14. G. Roche et al, Phys. Rev. Lett. 61:1069 (1988); C. Naudet, et al, submitted to Phys. Rev. Lett.; A. Letesier-Selvon, et al, submitted to Phys. Rev. C; G. Roche, et al , submitted to Phys. Lett. B
15. P. Lichard, private communication; V. Cerny, et al., Phys. Rev. D24:652 (1981)

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