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We discuss the physics objectives of the DLS program with some emphasis on the possible use of dileptons as a probe of pion dynamics in nuclear matter. Data on p+Be reactions at 1-5 GeV and Ca+Ca at 1 GeV/A are presented. The observation of a structure at twice the pion mass in the e^+e^- invariant mass spectra above 2 GeV beam energy and the excitation function for the p+Be reaction suggest that pion annihilation is the main dielectron source above 2 GeV. The dielectron mass spectrum from Ca+Ca at 1 GeV/A exhibits an inverse slope larger than the one from p+Be at the same beam energy.

The DLS Collaboration.
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Introduction.

The Dilepton Spectrometer (DLS) Collaboration has undertaken a program of measuring dielectron production in p-p, p-nucleus and nucleus-nucleus collisions at the LBL Bevalac:

$$A + B \longrightarrow e^+e^- + X \text{ (multiplicity measurement).}$$

Multiplicity information was not recorded with the first data presented herein. A multiplicity detector is being implemented on the experimental set up.

I am going to present the Physics objectives of the DLS program and discuss in particular the aspects relevant to pion dynamics in nuclear matter. The experimental set up will be very briefly described. First results on p+Be collisions at 1.0, 2.1 and 4.9 GeV beam energies and Ca+Ca at 1.0 GeV/A will be presented. I will end the talk with the conclusions obtained so far and the developments of the program.

Physics objectives.

Our main goal is the nucleus-nucleus study. However, it is needed to understand p-nucleus first. In fact, the p-nucleus study presents its own interest as it is shown below.

p-nucleus collisions.

The program aims to establish the existence of direct electron pair production in the few GeV beam energy domain and help clarify the production mechanism(s). Direct leptons are those not produced through the decay of known particles or resonances. Details on the subject can be found in ref. 1. I summarize the situation.

Direct leptons have been measured in inclusive experiments. In hadron-nucleus collisions above 10 GeV, the production yield of single direct electrons is found to be 10^{-4}, expressed in term of e/π ratio. However, two low energy measurements[2], pp at 256 and 800 MeV, have found no evidence for direct single electrons, at the level of $e/\pi = 10^{-6}$ for the 800 MeV measurement. This raises the question of a possible threshold in between 1 and 10 GeV.

The low mass continuum anomaly observed in high energy experiments for both dimuons and dielectrons of masses below 2 GeV is illustrated on Fig. 1. The low mass yield is well above Drell-Yan calculation estimates. This large yield is still poorly understood, even though soft parton model calculations for instance succeeded in reproducing some features of the rather scarce experimental data.

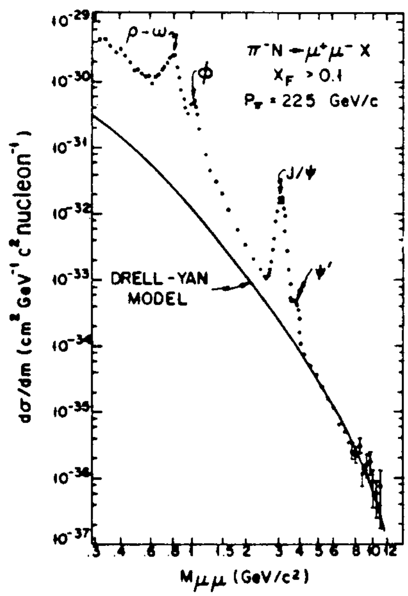


Fig. 1. Dimuon mass spectrum measured by the Chicago-Princeton group and contribution of the Drell-Yan process[3].

Nucleus-nucleus collisions.

When we submitted our first proposal four years ago, there was no theoretical study precisely relevant to the Bevalac energy range and obviously no available experimental data. We were leaning on general arguments as follows. Dileptons should be a good probe of the primary hot stage of the fireball. They present three advantages: (i) they are a penetrating probe and do not interact much in going out of nuclear matter, (ii) their production rate is biased towards the high density phase of the collision and (iii) their coupling to other particles is very well known. However, they present the disadvantage of low production rates due to the smallness

of the fine structure constant α (there is roughly one e^+e^- pair produced every several thousand NN collisions). This disadvantage actually makes the experimental difficulty quite serious.

Later on, Gale and Kapusta[4] have made calculations applicable to the Bevalac energy domain and pointed out possible interesting effects relevant to the pion dispersion relation in hot, dense nuclear matter. This study is generalized by L.H. Xia *et al.*[5] who include the expansion of the fireball and consider dileptons as a probe of pion dynamics in heavy ion collisions. G. Brown[6] discusses the interest of dilepton measurements in connection with the issue of the nuclear equation of state.

Pion dynamics in nuclear matter.

Gale and Kapusta[4] consider nuclear matter at given temperature T and baryon density n. Two possibly dominant contributions to the dielectron yield come from bremsstrahlung of the cascading baryons and $\pi^+\pi^-$ annihilation, both processes going to a virtual photon which subsequently decays into an e^+e^- pair. Among the three reactions pp, pn and nn between the cascading baryons, the most important bremsstrahlung source is from proton-neutron collisions because nn has no charged particle and pp is suppressed in the dipole limit. Pion annihilation proceeds through the ρ meson which decays into a virtual photon by vector dominance. Fig. 2 shows the dielectron production rates from both processes at normal nuclear density and at two different T values. The shape of the dielectron invariant mass spectrum appears to be very sensitive to temperature and pion annihilation dominates in the high mass region for the highest value of T. Being interested in pion dynamics, the $\pi^+\pi^-$ annihilation component is considered as the useful signal and bremsstrahlung as a background. So far, the pion dispersion relation has not been taken into account.

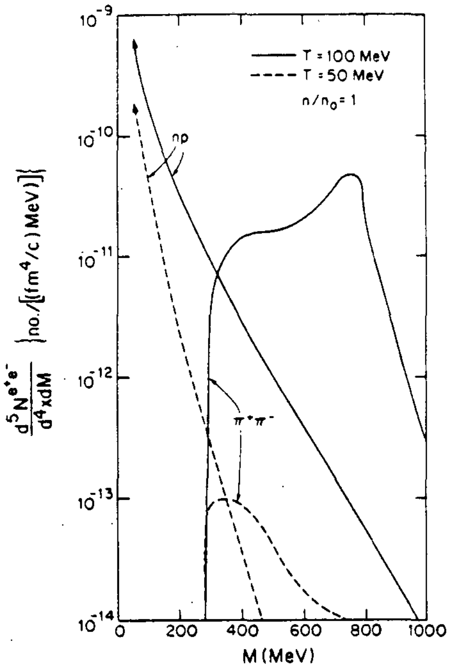
I would like to introduce the dispersion relation concept for a particle starting with the simple case of the propagation of light in a transparent medium. Far from absorption regions, the dispersion relation can be written as $n^2 = A + B/\lambda^2$. In this expression, n is the index of refraction and λ the wave length in vacuum, A and B being constants characteristic of the medium (electron density in particular). Instead of λ and n, we can use as well the photon frequency ω and its propagation vector in the medium $\mathbf{k}$. The dispersion relation is then a function of ω and $\mathbf{k}$, $f(\omega^2, \mathbf{k}^2) = 0$. When light propagates in vacuum, the relation is just $\omega^2 = \mathbf{k}^2$.

We can now go to the propagation of pions. In free space, we have the relativistic expression $\omega^2 = \mathbf{k}^2 + m_\pi^2$ where ω is the pion total relativistic energy and $\mathbf{k}$ its momentum. In nuclear matter, the dispersion relation is generally written as

$$\omega^2 = \mathbf{k}^2 + m_\pi^2 + \prod(\omega, \mathbf{k}).$$

The effect of the nuclear medium is introduced through the term $\prod(\omega, \mathbf{k})$. It is both temperature and density dependent, the strongest dependence coming from the baryon density. There is little experimental information on the pion dispersion

relation and it is mostly constructed on theoretical arguments[7]. Fig. 3 shows a qualitative representation of the pion dispersion relation in nuclear matter. It becomes softer with increasing density and may present a minimum for high enough densities.



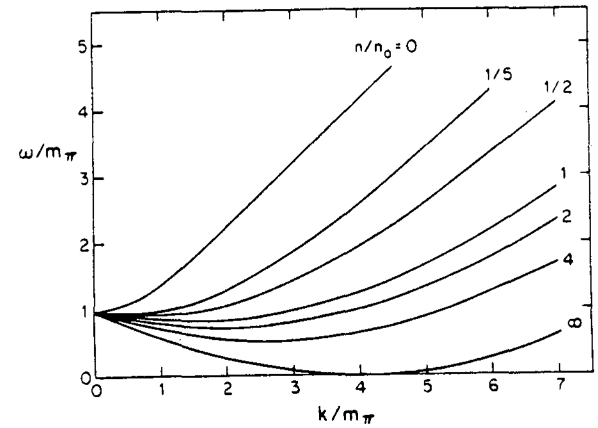


Fig. 3. A possible pion dispersion relation in nuclear matter[4].

Fig. 2. Dielectron production rates from ref. 4 (the pions have their free space dispersion relation).

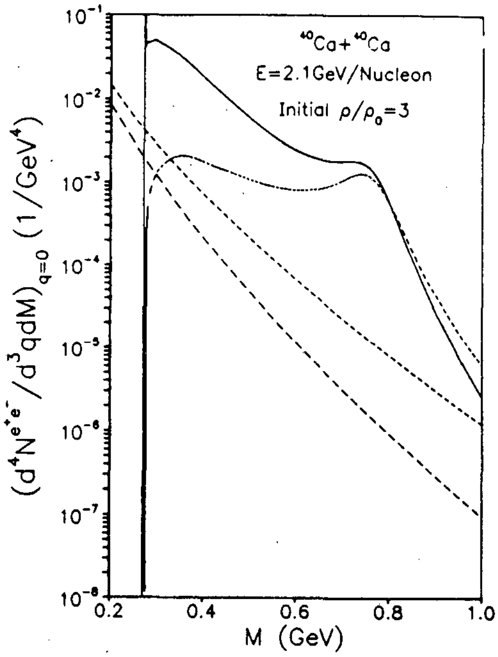
Gale and Kapusta[4] express the rate of production of back-to-back dielectrons ($\mathbf{q} = 0$) from $\pi^+\pi^-$ annihilation with the simple formula

$$\left.\frac{d^4R^{e^+e^+}_{\pi\pi}}{d^3q\,dM}\right|_{\mathbf{q}=0} = \frac{\alpha^2}{3(2\pi)^4}\frac{|F_\pi(M)|^2}{(e^{\omega/T}-1)^2} \times \sum_{\substack{k \\ \text{such that} \\ 2\omega(k)=M}} \frac{k^4}{\omega^4}\left|\frac{d\omega}{dk}\right|^{-1}$$

where the form factor $F_\pi(M)$ is for the ρ resonance. It is important to notice that the rate is proportional to the fourth power of k/ω and inversely proportional to the group velocity of the pion $d\omega/dk$. The effect of the pion dispersion relation is clearly seen on Fig. 4 from L.H. Xia *et al.*[5] (these authors make a more precise derivation of the dispersion relation than the one given in Fig. 3). The effect of the pion dispersion amounts to an enhancement of the mass region just above the $\pi^+\pi^-$ annihilation threshold by more than an order of magnitude.

As a conclusion to this first part of the talk, I can say that *dileptons should be a good probe of pion dynamics in nuclear matter. Notice that the same dispersion relation concept should actually apply to both p-nucleus and nucleus-nucleus collisions.*

Fig. 4. The effect of the pion dispersion relation on the dielectron production rate, solid curve. The dotted curve is the $\pi^+\pi^-$ annihilation contribution without dispersion effect. The other two curves are the contribution from pn bremsstrahlung computed in the soft photon approximation with phase space included (long dashed curve) or without (dashed curve). The figure is from ref. 5.



The dilepton spectrometer.

The DLS experimental set up (Fig. 5) consists of a segmented target and two symetric arms, each including a large aperture dipole magnet, three drift chambers, two segmented gas Cerenkov counters and two scintillator hodoscopes. Details can be found in ref. 8. The multiplicity array was not yet implemented when we collected the first data presented below. The kinematical domain under investigation is approximately 0.1-1.2 GeV in invariant mass, 0.0-0.8 GeV/c in transverse momentum and 0.5-1.9 in units of laboratory rapidity.

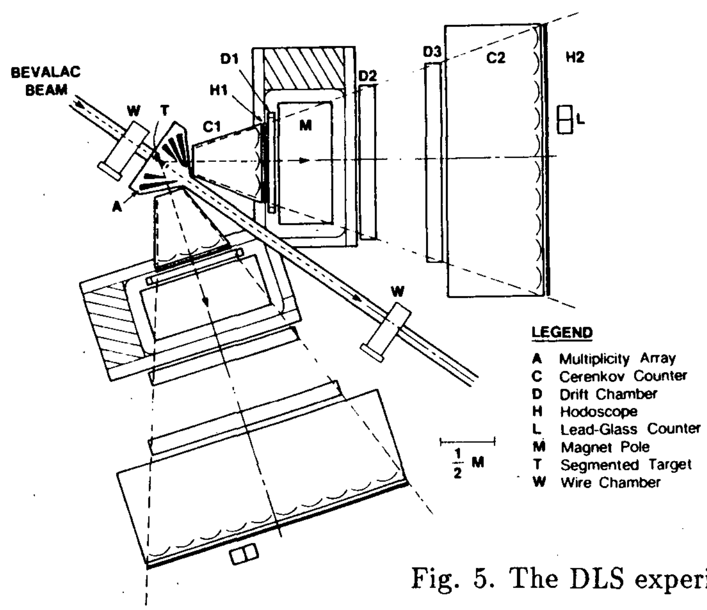


Fig. 5. The DLS experimental set up.

First results.

Table 1 gives the pair statistics for the data taken so far. The results at 1 GeV/A are still preliminary. The existence of a dielectron signal down to 1 GeV/A in both p+Be and Ca+Ca collisions is clearly established.

Table 1.

OS= number of opposite sign pairs, LS= number of like sign pairs, F= number of false pairs in the OS sample (F=LS), T= number of true pairs (T=OS−LS), $\sigma_T=\sqrt{OS+LS}$.

Reaction	OS	LS	T $\pm\sigma_T$	T/F	T/σ_T
p+Be at 4.9 GeV	732	201	531 ± 31	2.6	17.4
p+Be at 2.1 GeV	567	148	419 ± 27	2.8	15.7
Ca+Ca at 2.0 GeV/A	94	45	49 ± 12	1.1	4.2
p+Be at 1.0 GeV	263	111	152 ± 19	1.4	7.9
Ca+Ca at 1.0 GeV/A	731	476	255 ± 35	0.5	7.3

p+Be data.

The p+Be data at 4.9 GeV have been published.[8] In particular, the dielectron invariant mass spectrum[9] presents a decreasing continuum above 0.3 GeV with an enhancement in the ρ/ω region and a structure at about twice the pion mass (Fig. 6a). The region above 0.3 GeV agrees well in shape with the KEK data of Mikamo *et al.*[10] on p+Be at 12.1 GeV (Fig. 6b).

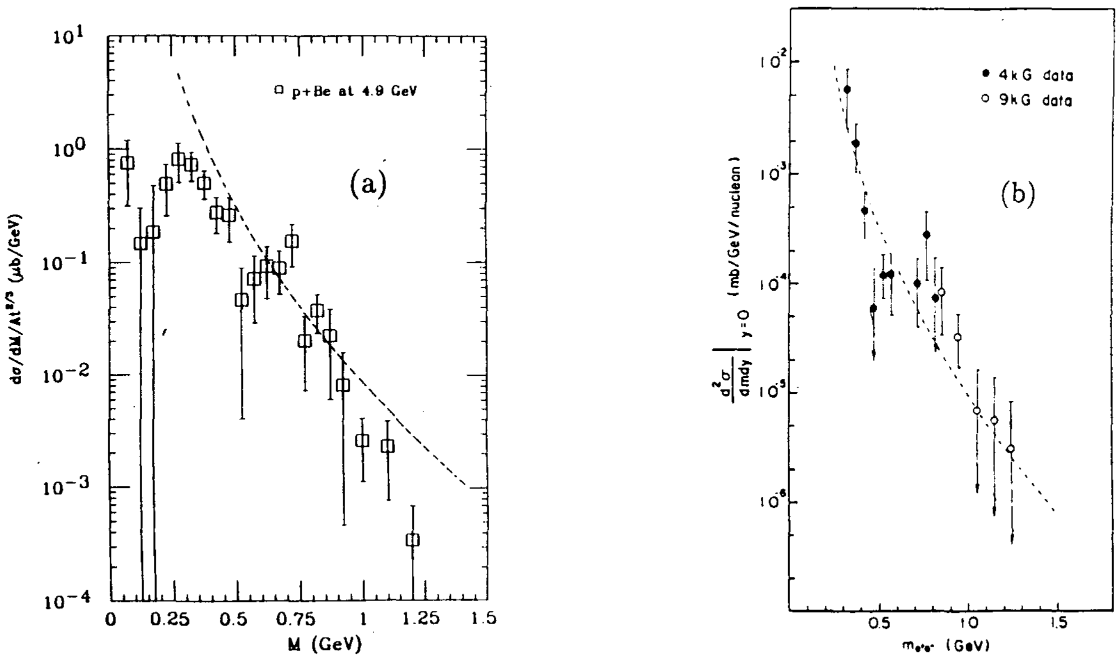


Fig. 6. Dielectron invariant mass spectra from the p+Be reaction. (a) The DLS data[8]. (b) The KEK data[10] at 12.1 GeV. For comparison of both data, the fit to the KEK spectrum (dashed line) is also shown with the DLS data.

The structure at twice the pion mass is also apparent in the DLS 2.1 GeV mass spectrum[11] but is not seen in the 1.0 GeV data that we will present below. It suggests that the main dielectron source at 2-5 GeV beam energies is pion annihilation. Another support to this first conclusion is given by the excitation functions shown in Fig. 7. Both the e^+e^- and $\pi^+\pi^-$ total cross sections are found to have similar threshold behavior while the π^0 total cross section is much flatter in the same range of available center-of-mass energy.

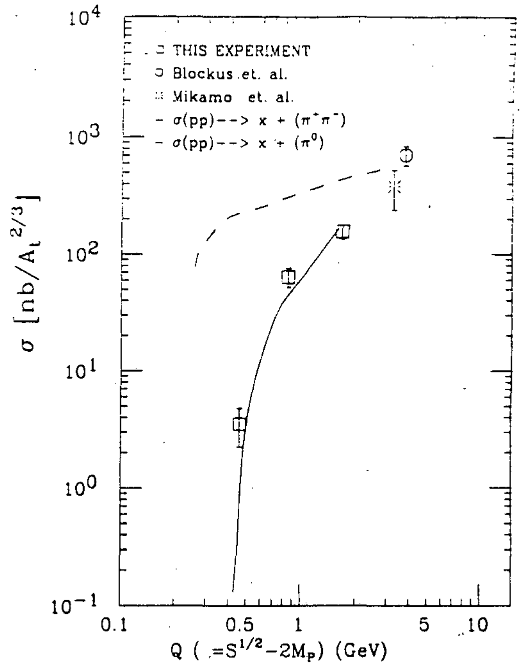


Fig. 7. The total dielectron production cross section as a function of the available NN center-of-mass energy: circle, Blockus *et al.*[12] π^-p at 16 GeV; star, Mikamo et al[10] p+Be at 12.1 GeV; squares, DLS data. The solid and dashed curves show the $\pi^+\pi^-$ and π^0 total cross sections[13] respectively, scaled down by 1.33×10^{-5}.

Ca+Ca data at 1 GeV/A.

Fig. 8a shows the dielectron invariant mass spectrum for the reaction Ca+Ca at 1.0 GeV/A. For comparison, a preliminary calculation by C.M. Ko[14] for the same reaction is shown in Fig. 8b (same type of calculation as in Fig. 4). The features of the computed spectrum (the brake at twice the pion mass and the ρ enhancement) are not seen in the experimental distribution. We can then try to just compare slopes. The exponential fit to the DLS spectrum yields an inverse slope of 142 $\pm$ 15 MeV. Hand-made exponential fits to the two components in Fig. 8b give inverse slopes of 95 and 69 MeV for pion-pion annihilation and bremmsstrahlung respectively, none of these numbers matching the experimental inverse slope which is much higher. However, two remarks have to be made. At this stage of the analysis, we have not yet estimated the main Dalitz decay contributions to the DLS data, namely π^0 and $\Delta(1232)$ Dalitz decays. Subtraction of these contributions is expected to mostly affect the low mass region of the experimental spectrum. The second remark refers to the calculation. It is performed for back-to-back pairs, i.e., pairs for which $p_t = 0$ and $y_{cm} = 0$. We do not have enough statistics in the DLS data to apply such cuts and, therefore, the comparison is quite uncertain.

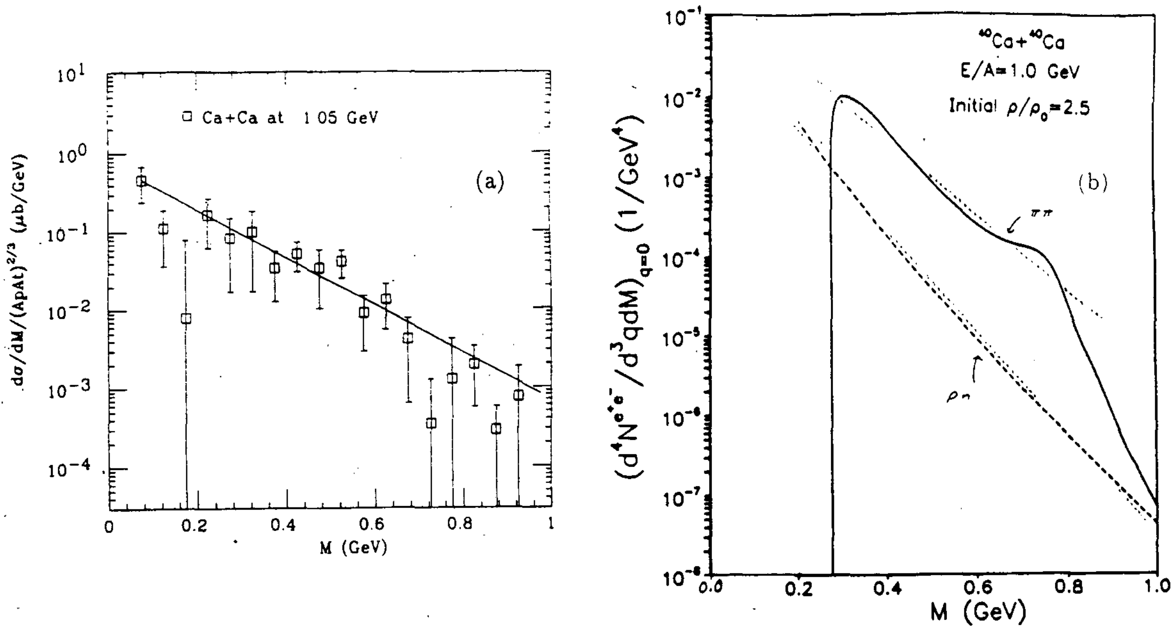


Fig. 8. (a) The dielectron invariant mass distribution from Ca+Ca at 1.0 GeV/A (DLS data); the solid line is an exponential fit to the data points. (b) For comparison, the rates of back-to-back pairs computed for pion-pion annihilation and pn bremsstrahlung[14]; the dotted lines are hand-made exponential fits to the annihilation and bremsstrahlung components.

Fig. 9 compares the dielectron mass spectra for both Ca+Ca and p+Be reactions at 1.0 GeV/A. Notice first that the p+Be spectrum is structureless within error bars (see above). There is a higher yield at higher masses in the Ca+Ca spectrum compared to p+Be. The exponential fit to the p+Be data yields an inverse slope of 75 ± 8 MeV, much lower than the Ca+Ca inverse slope of 142 ± 15 MeV. We can compute the total dielectron production yield for both reactions by integration of the mass distributions and look for a projectile/target mass dependence as $(A_pA_t)^\alpha$. For the whole mass range (0.05-1.00 GeV), we get $\alpha = 0.86 \pm 0.07$. Cutting off the mass bins below 0.20 GeV, we get $\alpha = 1.04 \pm 0.10$. The two numbers are compatible with each other and with the value $\alpha \approx 1$. Again, this comparison will be more interesting when we have subtracted Dalitz contributions.

Conclusion.

We have established the existence of a dielectron signal down to 1 GeV/A incident energy.

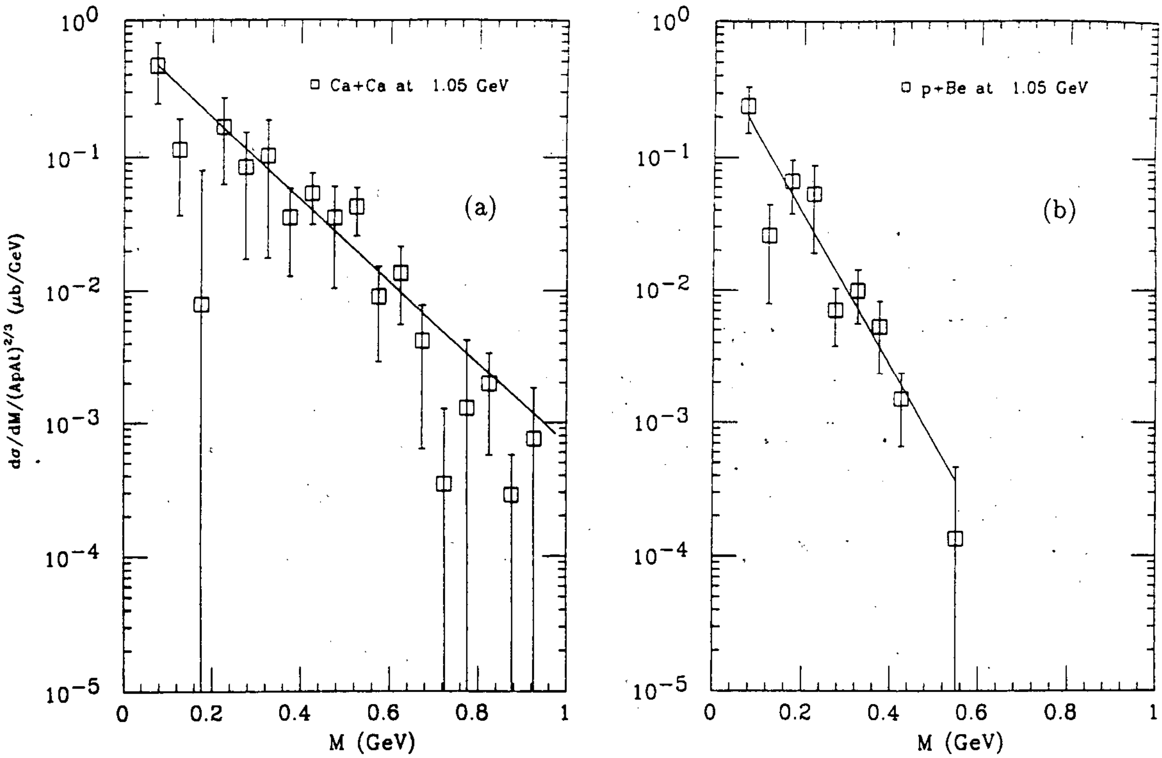


Fig. 9. Comparison of the dielectron mass distributions for both Ca+Ca and p+Be reactions. The solid lines are exponential fits to the data.

In p+Be collisions above 2 GeV, the mass distributions ($M_{e^+e^-} > 300 MeV$), p_t distributions and yields ($(e^+e^-)/(\pi^+\pi^-) \approx 10^{-5}$) are similar to those obtained at higher energies. The observation of a structure in the mass spectrum at about $2m_\pi$ and the excitation function suggest that annihilation of real pions is the dominant production mechanism.

Comparison of the Ca+Ca and p+Be data at 1 GeV/A shows a large difference in the slopes of the mass distributions, the Ca+Ca spectrum being much flatter. The production yields are consistent with a projectile/target mass dependence as $A_p A_t$.

There is hope to obtain information on pion dynamics in nuclear matter but it needs more work, both theoretical and experimental.

Developments of the program.

In the near future, we are going to take data on pp and pn reactions to further study the dielectron production mechanisms and, in particular, the 300 MeV mass structure. The multiplicity detector will be implemented for the next heavy ion runnings and we are planning to measure Ca+Ca or Nb+Nb reactions at 1 GeV/A.

On a longer term basis, the project should develop towards higher projectile/target masses at 1 GeV/A beam energy. It will most probably need an upgrade of the electron identification system.

Acknowledgements

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Footnotes and references

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[7]During the discussion following the talk, J.M. Moss, LANL, commented that there are experimental data that put constraints on the $g\prime$ constants used in the pion dispersion relation.

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[9]Throughout the paper, the DLS data are plotted as cross sections per nucleon, assuming an $(A_pA_t)^{2/3}$ mass dependence, where A_p and A_t are the projectile and target masses, respectively. This also holds for the KEK mass spectrum.

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