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# DILEPTON PRODUCTION IN NUCLEAR COLLISIONS AT INTERMEDIATE ENERGY[1]

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The understanding of the basic processes of dilepton production is improving owing to the large amount of data in p-p and p-d collisions from the DLS collaboration, and the on-going theoretical effort. The dilepton invariant mass spectra should be sensitive to medium effects, in particular in the vector meson mass domain, and to electromagnetic form factors in the time-like region.

## 1. Introduction

The laboratory energy domain under consideration is from about 1 to 10 GeV per nucleon. The presentation will be illustrated with experimental data from the DLS (DiLepton Spectrometer) program at the Lawrence Berkeley Laboratory's Bevalac. Except for the DLS data, there is in fact little experimental information available in the domain. Older experiments around 10 GeV incident energy [1] had quite low statistics and were concerned with the low-mass low-pt anomaly observed and studied in the late 70's/early 80's. Some indication on the HADES (High Acceptance DiElectron Spectrometer) project at SIS, Gesellschaft für Schwerionenforschung/Darmstadt, will also be given herein. For a more complete description of the project, see the presentation by H. Neumann [2].

The ultimate objective of both programs (DLS, HADES) is the use of dileptons (here $e^+e^-$ pairs) as a probe of the hadronic matter formed in the collision of relativistic heavy ions, and in particular the study of *in-medium properties of hadrons*. It is obvious that a good knowledge of the probe is needed first. The DLS collaboration has spent much time investigating the basic processes of dilepton production in the nucleon-nucleon interaction between 1 and 5 GeV (no data were available in this energy range). Interpretation of the results actually revealed a specific interest of the dilepton probe, namely its sensitivity to *electromagnetic form factors in the time-like region*.

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A brief description of the experimental technique will be given in the next section. The following two sections will be devoted to the basic processes of dilepton production in nucleon-nucleon collisions, and to the approach of hadronic matter and in-medium effects with the dilepton probe, respectively.

## 2. Experimental technique

The DLS collaboration [3] started its dilepton program in 1984 (date of the first proposal) and collected data in p-p and p-d, p-nucleus and nucleus-nucleus collisions (up to Nb-Nb) from 1986 to 1993. The data acquisition runs ended with the shutdown of the Bevalac in February of this year. The program will be completed within one to two years, with analysis and publication of the latest results.

The main experimental difficulty is the huge hadron flux. There is about one dilepton produced per 10,000 nucleon-nucleon collisions. In the DLS scheme [4], suitable hadron rejection power is achieved with two threshold Cherenkov counters adequatly segmented in each DLS arm. The rest of the system includes two dipole magnets and drift chambers for tracking, scintillator hodoscopes for redundant information and trigger purpose, a multiplicity detector around the target [5], and various detector calibration and beam control components.

A second difficulty, though less serious than the above one, is due to the combinatorial background, commonly referred to as *false pairs*. These result from two $\pi^0$ decays, directly through the Dalitz channel ($\pi^0 \longrightarrow \gamma e^+e^-$, BR = 1.2 %), or indirectly through the conversion of the real photons from the main channel ($\pi^0 \longrightarrow \gamma\gamma$; BR = 98.8 %). There are two electron pairs but, in some/many cases, one member in each pair is not seen by the detectors. The false $e^+e^-$ pairs cannot be identified on an event-by-event basis, but their contribution to the opposite sign sample can be accurately estimated from the measurement of the like sign pairs, $e^+e^+$ and $e^-e^-$, and then subtracted [6]. Obviously, the false pair background increases for heavier projectile/target systems. This background is improved by target segmentation and identification of the electrons as close as possible to the target, as implemented in both DLS and HADES designs.

## 3. Dilepton production in nucleon-nucleon collisions

### Basic processes and electromagnetic form factors

The main basic processes of dielectron production at intermediate energy are:

- two-body decays of vectror mesons ($\rho$,$\omega$,$\phi \longrightarrow e^+e^-$),
- three-body Dalitz decays of mesons ($\pi^0$, $\eta \longrightarrow \gamma e^+e^-$ and $\omega \longrightarrow \pi^0 e^+e^-$) and delta and nucleon resonances ($\Delta$,N* $\longrightarrow$ N$e^+e^-$),
- hadronic bremsstrahlung (pp,pn $\longrightarrow e^+e^- +$ X),
- and pion annihilation ($\pi^+\pi^- \longrightarrow e^+e^-$).



Table 1. Vector mesons.

| | M (MeV) | Γ (MeV - fm/c) | BR |
|---|---|---|---|
| $\rho$ | 770 | 149 - 1.3 | $4.4 \times 10^{-5}$ |
| $\omega$ | 783 | 8.4 - 23.5 | $7.1 \times 10^{-5}$ |
| $\phi$ | 1020 | 4.4 - 46 | $3.1 \times 10^{-4}$ |

Measurement of dileptons from two-body decays yield full information on the vector mesons themselves. Table 1 reproduces masses, widths and branching ratios for the three mesons. The $\rho$ and $\omega$ have about the same mass, but their width or life time are quite different. It follows that most of the time the $\rho$ will decay inside the interacting nuclear matter and the dilepton will carry out the information on its in-medium properties, namely any mass shift and/or width change. On the other hand, the $\omega$ will be much less affected (except perhaps for production yield) and can be used as a reference. This study is one of the main goals of the HADES project. A consequence is the need for a high resolution (in order to clearly see the $\omega$) and a high acceptance (cf. branching ratios). For a reason of production rate connected to a higher mass, the $\phi$ will be more difficult to study.

Dileptons from three-body decays do not provide full information on the parent. The $\pi^0$ Dalitz decay is not of great interest in our case because of the very low dilepton invariant mass (the average $e^+e^-$ mass is 15 MeV) and thus contributes mostly to the combinatorial background discussed in the previous section. Other three-body decays can be approached via model calculations, depending upon their contribution yields in the dilepton spectrum.

The pp/pn bremsstrahlung process turns out to be quite difficult to estimate. It will be discussed in some detail in the next subsections. Pion annihilation received much attention a few years ago and is still an interesting issue related to medium effect as will be shown later in the talk. This last process is actually connected to the $\rho$ behavior in nuclear matter via the pion electromagnetic form factor.

Dilepton production is described as the decay of a virtual/massive photon (labeled as $\gamma^*$) and all annihilation or radiative processes involve the coupling hadron-$\gamma^*$. The vector dominance model (VDM) states that the coupling is done via a neutral vector meson. Available electromagnetic form factor measurements are in good agreement with VDM for pions and in reasonnable agreement for etas [7]. This is not the case for baryons, which form factors have in fact been measured for nucleons only. The recent $p\bar{p}$ experimental data from LEAR [8] exhibits a significant deviation from the VDM calculation in the time-like region for $q^2 > 4m_p^2$. Furthermore, no data is available in the region relevant to our $q^2$ domain, around 1 GeV$^2$ (which is forbidden in $p\bar{p}$ experiments). Thus, *dilepton measurements should bring some information on baryon electromagnetic form factors in the time-like region* through pp/pn bremsstrahlung and $\Delta$ Dalitz decay as will be seen in the next subsections.

## The DLS experimental results

The first DLS data in p-Be between 1 and 5 GeV [9] were mostly interpreted in terms of pn bremsstrahlung, Δ decay and pion annihilation [10]. The bremsstrahlung from pp scattering was considered to be suppressed. The calculations indicated that pn bremsstrahlung is a dominant source for dielectrons, and increasingly with beam energy. A ratio as large as 10 for the dielectron yields in p-n and p-p interactions could be expected at 5 GeV. Furtermore, the pn bremsstrahlung calculations were considering only the "elastic channel" where the final state consists of the two nucleons and the dilepton, in contradiction with the fact that, at increasing energy, "inelastic channels" with produced pions contribute to most of the nucleon-nucleon cross section. These difficulties led the DLS collaboration to undertake measurements of p-p and p-d collisions (direct measurements of p-n collisions were not feasible).

Fig. 1 shows the normalized differential dielectron yields (number of dileptons per ion chamber count, one count being about $2 \times 10^6$ protons in the beam) as a function of invariant mass for the p-p and p-d systems at 1.0, 1.2, 1.6, 1.8, 2.1 and 4.9 GeV incident energies. It is seen that the shape and magnitude of the distributions for p-p compared to p-d are quite different at the lowest energies, below 2 GeV, and are rather similar within a factor of about two in magnitude at the two highest energies. These features are more apparent on fig. 2 where the dielectron yield ratios pd/pp are plotted as a function of invariant mass for the six beam energies. Obviously, the ratio should go to infinity (except for resolution smoothing) at the p-p kinematic limit because of Fermi momentum, but qualitatively one would expect a rather sharp effect. What is observed instead at the three lowest energies is a continuous increase as a function of mass which might be indicative of different processes at work. The ratio distribution at 2.1 GeV is unexpectedly flat up to the kinematic limit.

Fig. 3 presents the two excitation functions of the integrated yield ratio pd/pp for masses below 100 and above 150 MeV, respectively. The low mass ratio has a rather flat behavior, going down smoothly from about 3 to 2. This mass range is essentially populated by $\pi^0$ Dalitz decay (true) dielectrons, and the DLS ratios about 1 GeV are actually in agreement with an inclusive measurement of the $\pi^0$ cross sections in p-p and p-n by A.P. Batson [12] which yields a pd/pp ratio of $4.1 \pm 0.8$ (the open circle in the figure). The excitation function for M > 150 MeV (no $\pi^0$ contribution) exhibits a drastic change in between 1 and 2 GeV, going down from about 10 to 2 with increasing energy. The $\eta$ and $\rho$-$\omega$ nucleon-nucleon thresholds are indicated by arrows on fig. 3. It would be interesting to have another point below 1 GeV to see if the excitation function (M > 150 MeV) is really flattening off at low energy.

Finally, associated hadron-dilepton events in the DLS have been analyzed for some of the above dilepton measurements [13]. It is found that there are about $3 \pm 1$ % pion-dilepton event above 2 GeV beam energy, and a preliminary estimate of the corresponding pion production yield in the whole phase space per detected dilepton amounts to $40 \pm 20$ %.

These experimental results in p-p and p-d clearly establish that the pn bremsstrahlung process as estimated in the first model calculations is not a dominant source, at least above 2 GeV beam energy, and that pp is not suppressed.



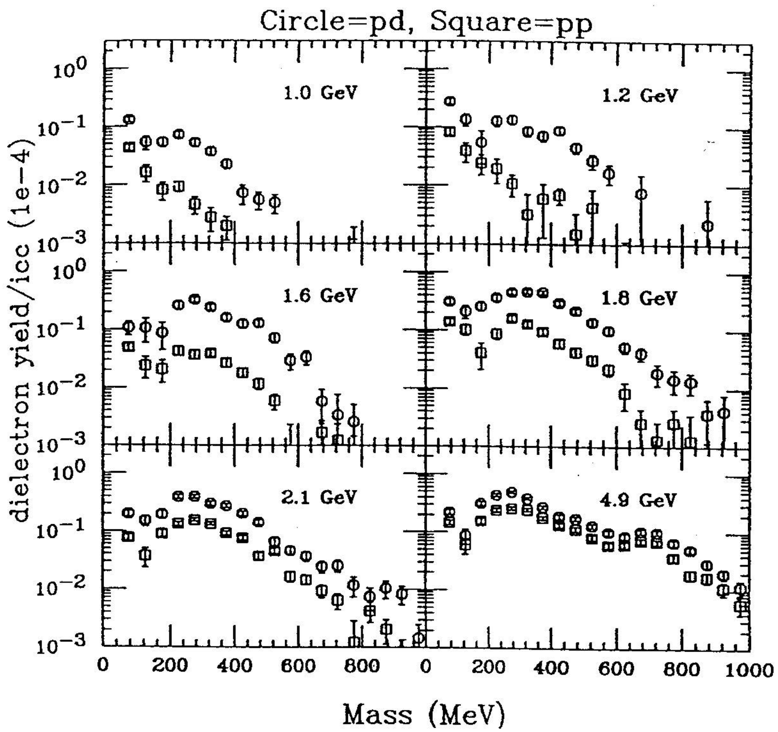


Fig 1. Comparison of dielectron invariant mass distributions in p-p and p-d collisions at six beam energies between 1.0 and 4.9 GeV.

## Inelastic nucleon-nucleon bremsstrahlung

In this subsection, we are going to focus on pn/pp bremsstrahlung calculations. The pn process has been first computed in the soft photon approximation [10] that retains only radiation from external charged lines, treats the strong interaction blob as being on shell, and makes use of the elastic nucleon-nucleon cross section. The pp process is neglected considering the non-relativistic dipole limit. Energy conservation is taken care of with the aid of a phase space correction factor. Later on, covariant computations of the pn process were performed in the one-boson-exchange description of the nucleon-nucleon interaction [14]. The results were found to be in reasonable agreement with those from the soft photon approximation and no further attempt of covariant calculations were undertaken. Recently, L.A. Winckelmann et al. [15] pointed out that the forward peaking of the differential elastic pn cross section gives a reduction of about a factor of 3 of the dilepton yield compared to the previously used symmetric parametrization at 4.9 GeV beam energy. B. Kämpfer et al. [16] studied off-shell and VDM form factor corrections and obtained pd to pp ratios consistent with the DLS data at 4.9 GeV. The more recent work by K. Haglin and C. Gale [17]

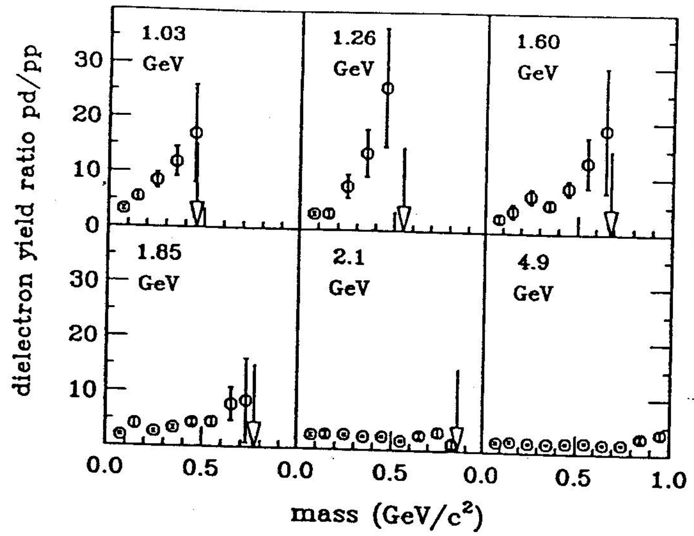


Fig 2. The pd/pp ratios as a function of the dielectron invariant mass. The maximum dielectron mass kinematically allowed in p-p collisions is indicated by an arrow for each beam energy except 4.9 GeV, where the limit, M = 1.7 GeV, is off-scale. The figure is from W.K. Wilson et al. [11].

introduces the concept of inelastic nucleon-nucleon bremsstrahlung and we examine now some of their results.

These authors use the soft photon approximation that includes radiation from all external charged lines of multi-hadron final states. They first investigate the electromagnetic weightings for the pp and pn elastic interactions and find they are of comparable magnitude at 4.9 GeV, while at 0.1 GeV pn dominates pp by about a factor of 10, in agreement with the dipole limit. Then accurate parametrizations of the differential elastic cross sections lead to the interesting result that the dilepton yield at 4.9 GeV is larger for pp than for pn, both being much lower than the experimental measurements from the DLS. Contributions from the inelastic channels with one, two and three pions in the final state are found to drastically increase the dilepton yield, with a resulting mass distribution getting steeper than for the elastic channel. Their overall result for p-p at 4.9 GeV, including inelastic bremsstrahlung, $\eta$ and $\Delta$ Dalitz decays, and pion annihilation, shows reasonnable agreement with the DLS data. However, the intermediate mass region around 400 MeV is underestimated by about a factor of 3. More work is needed, perhaps the inclusion of form factors in the $\eta$ Dalitz decay and the bremsstrahlung. If hadronic processes are not enough, then one might think of parton mechanisms [18].

In conclusion of this section, one can say that the large amount of DLS data and the on-going theoretical effort should result in adequate understanding of the dilepton probe to be used in the study of nuclear matter.



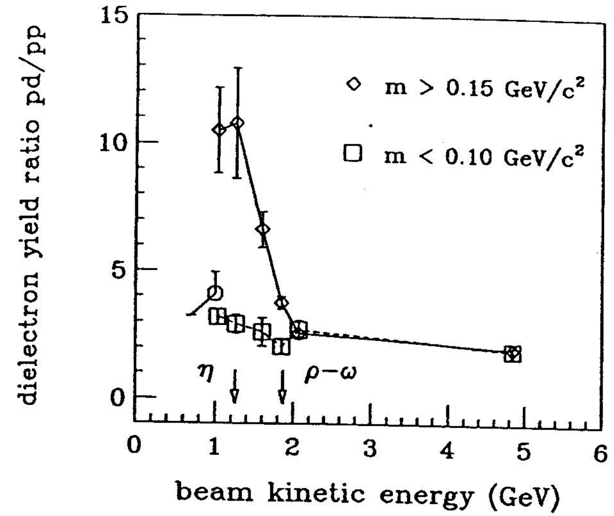


Fig 3. The pd/pp ratio as a function of the beam energy for dielectrons in the mass region dominated by $\pi^0$ Dalitz decay, $50 < M < 100$ MeV (squares), and the rest of the mass spectrum, $M > 150$ MeV (diamonds). The beam energy thresholds for $\eta$ and $\rho$-$\omega$ production are indicated by the two arrows. The lines are only to guide the eyes. The figure is from W.K. Wilson et al. [11].

## Hadronic matter and dileptons

### General aspects

In the temperature-baryon density phase diagram of nuclear matter (see fig. 4), the domain under investigation here covers temperatures about 100 MeV and baryon densities in the range of 3 to 8 times normal density (for beam energies from about 1 to 10 GeV/A). This is the domain of hadronic matter, sometimes referred to as "hadron gas", in which the hadronic degrees of freedom are suitable to describe the medium properties. Nevertheless, there is indication from first estimates that QCD underlying effects (partial restoration of chiral symmetry) could be observable at rather low temperature and smoothly increasing baryon density, while at low baryon density, temperature has to reach its critical value (about 200 MeV) before a sharp discontinuity should occur, a scenario attainable with ultrarelativistic heavy ion beams. We will get to this point in the next subsection.

The main reason for using dileptons in the study of hadronic matter is that it is a *penetrating electromagnetic probe*. The current well established description of relativistic heavy ion collisions, best seen in central collisions of symmetrical systems, introduces an initial stage at high temperature and high baryon density (due to stopping of matter) followed by an expansion and cooling stage that ends with the emission of hadrons (freeze out). Thus, direct information on the initial stage cannot be obtained with hadronic probes, and there is need for a reconstruction of the whole

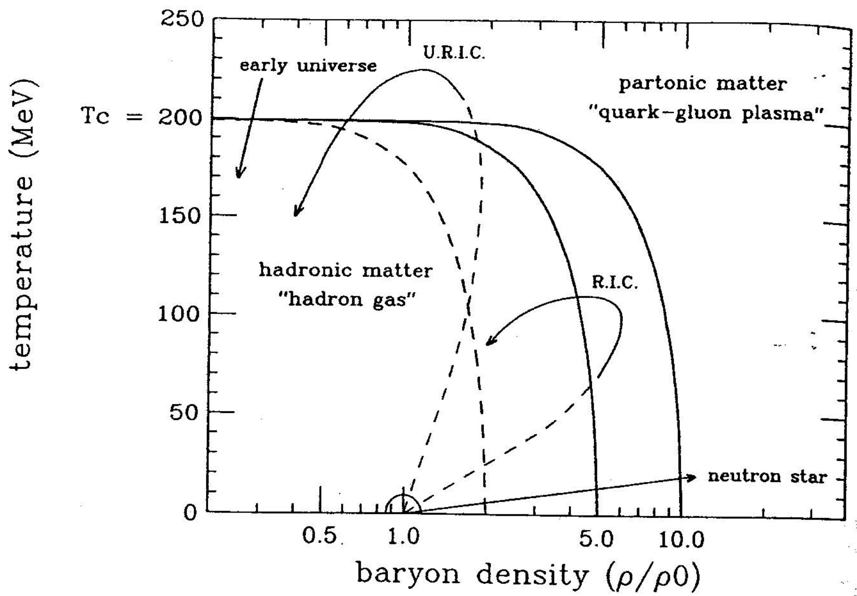


Fig 4. Temperature-baryon density phase diagram of nuclear matter. The thick solid lines define a region where deconfinement might occur and a mixed phase be produced. The thick dashed line figures a boundary for partial restoration of chiral symmetry. The thin dashed-solid lines represent relativistic and ultrarelativistic heavy ion collision paths, labeled R.I.C. and U.R.I.C. respectively.

history of the collision with the aid of simulation codes (BUU, QMD,...). In contrast, dileptons can leave the high density interaction region without sizeable disturbance and provide a signal on the initial stage. Table 2 illustrates the comparison between electromagnetic and hadronic probes.

The first DLS data in p-Be [9] and Ca-Ca [20] are sometimes interpreted without medium effect. General features from model calculations [15-21] are: (1) the low mass region below 400 MeV is mostly populated by $\eta$ Dalitz decay, (2) the bremsstrahlung and $\Delta$ decay dominate in the intermediate mass range (400 to 600 MeV) in p-Be at 2.1 GeV which makes this mass region sensitive to electromagnetic form factors and suitable to VDM tests, and (3) the highest mass domain above 600 MeV in Ca-Ca collision is the cleanest with only one dilepton production mechanism at work, pion annihilation, making this mass domain particularly attractive to medium effect studies, as will be discussed in the next subsection. However, the above conclusions do not apply to p-Be at 1.0 GeV where the bremsstrahlung and $\Delta$ contributions dominate over the whole mass range (above 100 MeV).



Table 2. Particle production around 1 GeV/A [19].

| | $\sigma$ production | $\sigma$ reaction | mean free path in nuclear matter |
|---|---|---|---|
| pion | 5 mb | 100 mb | 0.5 fm |
| eta | 0.2 mb | 50 mb | 1 fm |
| kaon | 50 $\mu$b | 10 mb | 5 fm |
| antikaon | 20 $\mu$b | 40 mb | 1 fm |
| anti proton | 0.5 $\mu$b | 100 mb | 0.5 fm |
| photon | 50 $\mu$b | | $\infty$ |
| dilepton | 0.5 $\mu$b | | $\infty$ |

## In-medium effects

The interest of dileptons to study medium effects was first pointed out by C. Gale and J. Kapusta and made more quantitative by L.H. Xia et al. [22]. At the time, the emphasis was put on the dispersion of pions in nuclear matter. These first estimates indicated a drastic enhancement of the dilepton yield close to the mass threshold ($2m_\pi$) because of the softness of the dispersion relation in the nuclear medium. The mass threshold could actually shift below its value in vacuum (279 MeV) at density high enough when the relation presents a minimum. Later on, C.L. Korpa and S. Pratt realized that inclusion of medium effect on the pion annihilation vertex would strongly reduce the enhancement previously estimated. A more precise calculation by C.L. Korpa et al. [23] taking into account finite dilepton momenta (in the collision rest frame) and delta width, still reports a quite substantial enhancement and threshold shift.

Nowadays, the theoretical effort has moved towards the pion electromagnetic form factor and the behavior of the $\rho$ meson in the nuclear medium. Recent works [24] show that the peak position is slightly shifted to high mass vith increasing density, and the resonance is significantly weakened. There may be a structure about a mass value of 400-500 MeV. Gy. Wolf et al. [21] put the medium corrected pion form factor in their BUU calculation. Fig. 5 shows their results for Ca-Ca at 1 GeV/A and p-Be at 2.1 GeV, and the density dependent form factor from M. Herrmann et al. they use. For the Ca-Ca collision, the dashed line labeled "background" is the sum of all contributions other than pion annihilation, the dotted and solid lines are the annihilation contributions with free space and density dependent form factors, respectively. The dilepton yield at the $\rho$ mass of 770 MeV is reduced by a factor of 4 when medium correction is introduced. For p-Be, the authors try to estimate the medium modification of the pn bremsstrahlung component by simply using the same form factor as for pions. In the figure, "background" refers now to all processes other than pn bremsstrahlung, the dotted line is the bremsstrahlung estimate without a form factor, and the dashed and dot-dashed lines show the effects of free space and medium corrected form factors, respectively. One observes a huge increase of the dilepton yield when the form factor is introduced, more than one order of magnitude, and then again a quite sizeable reduction in the $\rho$ mass region due to medium correction. The DLS experimental points in the figure qualitatively support medium correction and clearly emphasize the need for high statistics data.

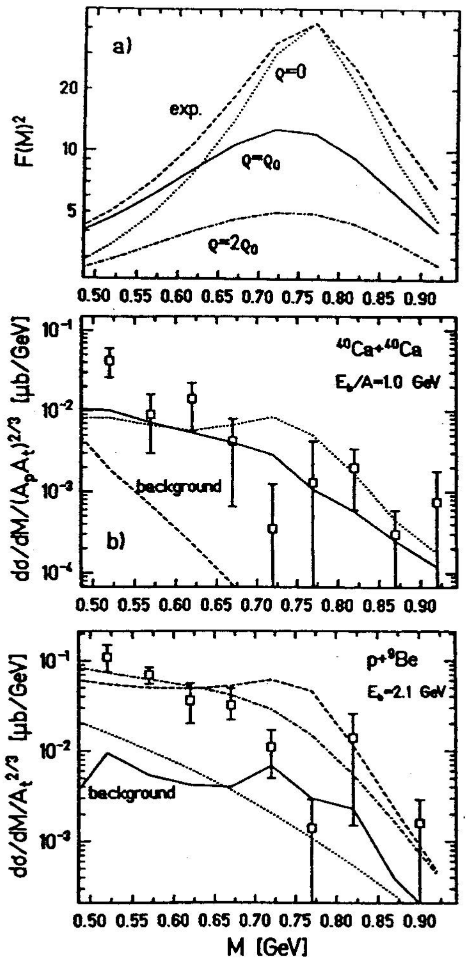


Fig 5. a) The electromagnetic form factor of the pion as a function of density (from M. Herrmann et al.). b) In-medium changes of the pion annihilation component for Ca-Ca at 1 GeV/A. c) Effects of the proton form factor on the dilepton spectra for p-Be at 2.1 GeV. See text for an explanation of the different lines. The figure is from Gy. Wolf et al. [21].

The above medium modification estimates are based on a hadronic description of the propagation of the rho meson in nuclear matter. QCD related approaches have also been used [25] and seem to indicate that QCD vacuum modification and partial restoration of chiral symmetry could be observed at low temperature and finite baryon density ($\rho \neq 0$), which could actually be a better place than the finite temperature system with $\rho = 0$. In a consistent treatment of QCD sum rules in the nuclear medium,



T. Hatsuda and S.H. Lee obtain a linear reduction of the vector meson masses valid in the density domain below about 2 times the normal nuclear matter density $\rho_0$. Even at moderate density, the mass reduction would be quite impressive. For instance, the rho-omega mass would go down by 200 MeV at $\rho/\rho_0 = 1.5$. At the same density, the phi mass would be below the threshold of its main $K\bar{K}$ decay mode (if the kaon mass does not change in medium), which could be checked by comparison to the dilepton decay mode. In addition to the above mass shift, M. Asakawa and C.M. Ko report a reduction in the rho width as the nuclear density increases. These modifications of the rho meson obviously react on the dilepton mass distributions and would be easily observable.

All theoretical calculations indicate that dilepton invariant mass spectra are sensitive to medium effects, in particular in the $\rho/\omega$ mass region. They may still look uncertain, and probably more so for the QCD sum rules approach, but they clearly call for high statistics and high resolution experimental data.

### The latest DLS data

The DLS collaboration is analyzing the latest runs at 1 GeV/A with various light ion beams and targets. Fig. 6 shows preliminary mass distributions for C-C and Ca-Ca collisions. The statistics in the Ca-Ca spectrum is about 10 times higher than in the first measurement reported before in the article, and will be doubled when the analysis is completed. Exponential fits of the mass spectra between 200 and 600 MeV yield inverse slope values of 100 ± 3 and 180 ± 10 MeV, for C-C and Ca-Ca, respectively. This significant change in slope was previously observed, with less accuracy, for the p-Be and Ca-Ca systems [20]. It must be noticed that the difference between the old and new slope numbers for Ca-Ca is mostly due to the analysis (difference in the cuts that are used in the acceptance correction). It is stressed also that the new numbers may change when full analysis is completed. Finally, the figure supports our previously published scaling result for the integrated cross section [5], i.e., $\sigma \sim (A_p A_t)^\alpha$ with $\alpha \approx 1$.

## 6. Conclusions and outlook

Elementary processes of dilepton production at intermediate energy should be hadronic: decays of particles and resonances or bremsstrahlung and annihilation. Dalitz decays and bremsstrahlung/annihilation are subject to hadron-$\gamma^*$ coupling. Two body decays of vector mesons and pion annihilation seem to be of main interest in relativistic heavy ion physics. Dalitz decay of the $\Delta$ resonance and nucleon-nucleon bremsstrahlung can provide information on the baryon electromagnetic form factors in the time-like region where no data exist.

The large amount of DLS data in p-p and p-d collisions between 1 and 5 GeV and the on-going theoretical effort should result in an adequate understanding of the basic cross sections of dilepton production to be used in the simulation codes of relativistic heavy ion collisions. Sometimes, comparisons of experimental data and models are done for mass spectra only, as these look more promising for medium effect studies. It

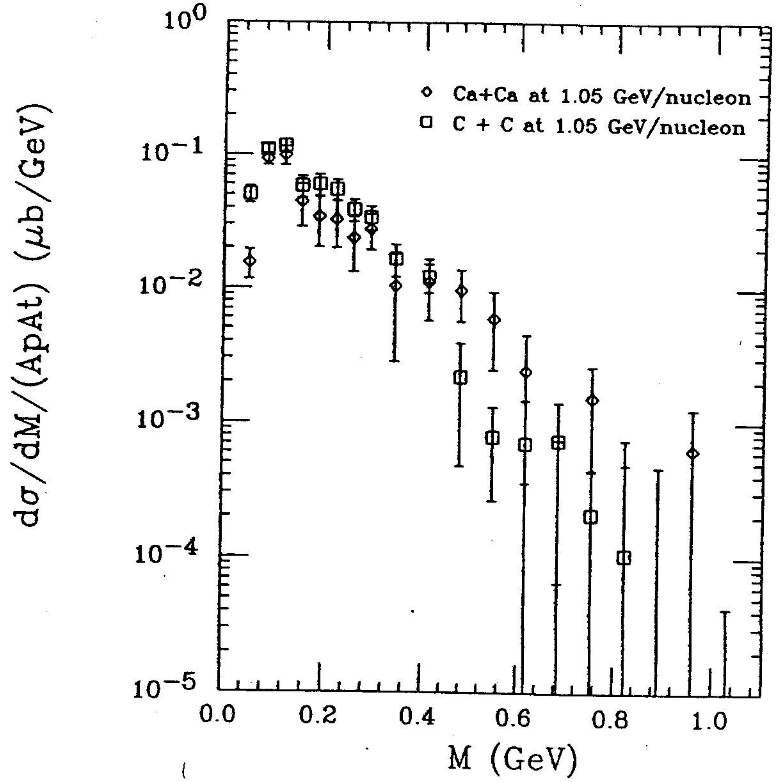


Fig 6. The new DLS dielectron mass distribution measurements on C-C and Ca-Ca collisions at 1 GeV/A.

must be stressed that the measured $p_t$ and $y$ cross sections are also useful to constrain the models. Moreover, *any accurate comparison implies that the DLS acceptance filter is included in the cross section calculations.*

Dileptons, a penetrating electromagnetic probe, are appropriate to the study of the hot and dense hadronic matter formed in relativistic heavy ion collisions. One may distinguish two regions in their invariant mass spectrum, the one below 500-600 MeV, mostly populated by Dalitz decays and bremsstrahlung, more complex to interpret, and the other above, more simple, where pion annihilation and vector meson two-body decays dominate, more sensitive to medium effects. Calculations of in-medium properties, based on hadronic or QCD related approaches, are rather uncertain and/or present significant discrepancies. There is an obvious need for experimental data.

The first DLS measurements in nucleus-nucleus collisions are in qualitative agreement with hadronic models of the propagation of the $\rho$ vector meson in nuclear matter, and they clearly show the importance of high statistics and high resolution experiments. The recently collected data in C-C and Ca-Ca at 1 GeV/A have much better statistics. They show a significant change in slope of the mass distributions from C-C to Ca-Ca. The first data presented a similar feature, with less accuracy, but from p-Be to Ca-Ca.



The HADES detector is designed to achieve a very high acceptance, 40 % in the collision frame, and good resolution, adequate to unambigously identify the $\rho$ and the $\omega$. Its main goal will be a high statistics study of the vector mesons for projectile-target systems up to Au-Au, at 1 - 1.6 GeV/A.

It would also be of great interest to perform measurements in the energy range around 10 GeV/A, where the vector meson cross sections are higher by more than two orders of magnitude, and the baryon density is estimated to reach values about 7 - 9 times normal nuclear density, compared to about 3 times at 1 GeV/A. There may however be a drawback in that the low mass continuum becomes more complex.

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