# DILEPTON PRODUCTION: A TOOL TO STUDY VECTOR MESONS IN FREE SPACE IN NUCLEI AND IN NUCLEUS–NUCLEUS COLLISIONS*

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*(Received December 8, 1995)*

The decay of vector mesons into lepton pairs ($e^+e^-$ or $\mu^+\mu^-$) offers a very nice channel to study their relation to time-like photons in free space and their properties in the nuclear medium, as the emitted leptons are not distorted by strong interactions. This paper summarizes the known aspects of vector meson physics, discusses some recent theoretical developments and indicates the new experimental perspectives opened in this field by large acceptance dilepton detectors.

PACS numbers: 21.65. +f, 11.40. Fy

## 1. Introduction

The decay of a vector meson into a lepton pair, $e^+e^-$ or $\mu^+\mu^-$, is a wonderful phenomenon. It converts a complicated, strongly interacting hadron resonance into a pair of simple, elementary particles, interacting only very slightly with matter, in a way precisely given by perturbative quantum electrodynamics. It is a rare phenomenon, with branching ratios of the order of a few times $10^{-5}$ for the lowest-lying vector mesons, but not so rare that it precludes experimental observation.

Vector mesons convert into massive photons which materialize into lepton pairs, because vector mesons and photons have the same quantum numbers: they are spin 1 objects. The lightest vector mesons are the $\rho(770)$, the $\omega(782)$ and the $\phi(1020)$ mesons. They appear dominantly as $2\pi$, $3\pi$ and $K\overline{K}$ resonances respectively and are described as $q\overline{q}$ states in the quark

* Presented at the XXIV Mazurian Lakes School of Physics, Piaski, Poland, August 23–September 2, 1995.

model. Their basic properties are recalled in Section 2. Because of this mixing with virtual photons, vector mesons play a very important role in electromagnetic form factors of hadrons in the low $q^2$ regime ($|q^2| \leq 1$ GeV$^2/c^2$). A simple theoretical assumption, the Vector Dominance Model (VDM) [1, 2], states that virtual photons couple to hadrons by first converting to a vector meson which couples in turn to the hadron. We present this model and its limitations in Section 3, together with interesting prospects for making new measurements of hadron electromagnetic form factors in the time-like region by combining the planned pion beam and the HADES detector at GSI. Section 4 is devoted to a theoretical discussion of the properties of vector mesons in the nuclear medium and, in particular, to the most interesting suggestion that vector mesons could be order parameters for chiral symmetry restoration at high baryon density (or temperature) [3]. In Section 5, we discuss ways to measure vector meson masses in nuclei. Experiments in which vector mesons are produced near threshold and observed by their dileptonic decay appear as the most promising processes for such measurements. We mention some theoretical problems which need to be solved in order to be able to give a proper interpretation of these experiments, which can be performed at CEBAF with the CLAS detector and at GSI with HADES. Section 6 deals with the production of dileptons in heavy ion collisions, where matter at high baryon density or high energy density is produced. The spectrum of lepton pairs is expected to be significantly distorted by changes in vector meson properties in such environment. We discuss briefly the perspectives of $e^+e^-$ pair measurements in relativistic heavy ion collisions (at GSI with the HADES detector) and recent data obtained at ultra-relativistic energies (at CERN with the CERES detector) [4]. We conclude by a few remarks in Section 7.

## 2. Basic properties of vector mesons

The vector mesons which play a role in the low $g^2$ regime that we discuss in this lecture ($|q^2| \leq 1$ GeV$^2/c^2$) are those having masses $\leq 1$ GeV, *i.e.* the $\rho(770)$-, the $\omega(782)$- and the $\phi(1020)$-mesons mentioned earlier. The $\rho$-meson is a vector-isovector meson and has therefore 3 charge states ($\rho^+, \rho^0, \rho^-$). The $\omega$ and $\phi$ are (neutral) vector-isoscalar mesons. The $\rho$- and $\omega$-mesons, which have almost degenerate masses, are made of u and d quarks. The $\phi$-meson is made of strange quarks.

The $\rho$- and the $\omega$-mesons differ not only by their isospin but also by their $G$-parity, which is $+1$ for the $\rho$ and $-1$ for the $\omega$. Because of this, and recalling that the $\pi$-meson has $G$-parity $-1$, the $\rho$-meson decays dominantly into 2 pions ($\sim$ 100%) and is very broad [ $\Gamma_\rho = (151.2 \pm 1.2)$ MeV ]. For later purposes, let us also mention a small $\rho^0 \to \pi^0\gamma$ branching ratio of

$(7.9 \pm 2.0) \times 10^{-4}$ and the value of the $\rho^0 \to e^+e^-$ branching ratio of $(4.46 \pm 0.21) \times 10^{-5}$. By the same $G$-parity argument, the $\omega$-meson decays dominantly into 3 pions ($\sim$ 89%) and, because of phase space limitations, is much narrower than the $\rho$-meson [ $\Gamma_\omega = (8.43 \pm 0.10)$ MeV ]. The $\omega \to \pi^0\gamma$ branching ratio of $(8.5 \pm 0.5)$ % is substantially larger than the value associated to the corresponding channel for the $\rho$-meson and the branching ratio for $\omega \to e^+e^-$ is $(7.15 \pm 0.19) \times 10^{-5}$. The $\phi$-meson decays dominantly ($\sim$ 83%) into $K\bar{K}$. It has $G$-parity -1 and, therefore, the main nonstrange decays are the $\rho\pi$ (12.9%) and $3\pi$ (2.5%) channels. The $\phi$-resonance, being quite close to the $K\bar{K}$ threshold ($M_K$=494 MeV), is very narrow [ $\Gamma_\phi = (4.43 \pm 0.06)$ MeV ]. The $\phi \to e^+e^-$ branching ratio is $(3.09 \pm 0.07) \times 10^{-4}$. More details on vector meson branching ratios and the numbers given above can be found in Ref. [5].

## 3. Electromagnetic form factors of hadrons — the Vector Dominance Model: present status and prospects for new measurements

Hadrons are extended objects made of confined quarks and gluons. The coupling of hadrons to virtual ($q^2 \neq 0$) photons as function of $q^2$ (the form factors) reflects the electromagnetic structure of these composite objects and in particular their electromagnetic size.

Experimentally, electromagnetic form factors of hadrons are measured either in elastic electron scattering experiments or in dileptonic decays and annihilations ($e^+e^-$ or $\mu^+\mu^-$). In the case of elastic electron scattering experiments, the exchanged photon which carries the momentum transfer is space-like ($q^2 < 0$). The dileptonic decay or annihilation processes involve time-like photons ($q^2 > 0$). The coupling to real photons fixes the $q^2 = 0$ limit.

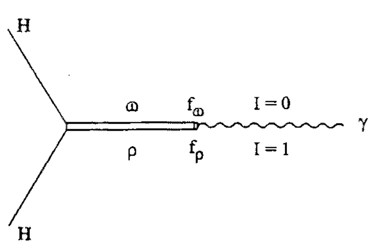


Fig. 1. The Vector Dominance Model of photon-hadron couplings.

It has been proposed by Sakurai [1] that the conversion of virtual photons into vector mesons provides a model of the electromagnetic structure of hadrons in the long wavelength limit ($|q^2| \leq 1\mathrm{GeV}^2/c^2$). This assumption, known as the Vector Dominance Model (VDM), states that virtual photons in that $q^2$ domain couple to hadrons through intermediate vector mesons. This is illustrated in Fig.1. To lowest order, the isoscalar part of the electromagnetic current couples through the $\omega$-meson and the isovector part through the $\rho$-meson [2]. The coupling constants for the conversion of photons into vector mesons are dimensional and go like the square of vector meson masses,

$$f_V = \frac{eM_V^2}{2g_V}, \tag{1}$$

in which $g_V$ is a dimensionless quantity. The numerical values of $f_\rho$ and $f_\omega$ can be derived from the $e^+e^-$ decays of $\rho$- and $\omega$-mesons,

$$f_\rho = 0.0355 \text{ GeV}^2, \tag{2}$$

$$f_\omega = 0.0109 \text{ GeV}^2. \tag{3}$$

In this simple model, the effective size of photon-hadron vertices is determined by the vector meson propagator and the $q^2$-dependence of the corresponding electromagnetic form factors is given by

$$F_H(q^2) = \frac{M_V^2}{M_V^2 - q^2 - iM_V\Gamma_V(q^2)}, \tag{4}$$

where $\Gamma_V$ is the total vector meson width, a $q^2$-dependent quantity. It vanishes for example below the $2\pi$ threshold for the $\rho$-meson. For $q^2 = 0$, $|F_H(q^2)|^2 = 1$, reflecting the charge. For $q^2 < 0$, $|F_H(q^2)|^2$ decreases with increasing $|q^2|$. For $q^2 > 0$, $|F_H(q^2)|^2$, has a resonance shape determined by the mass and width of the intermediate vector meson. The Fourier transform of Eq. (4) gives the hadron charge distribution in the Vector Dominance Model.

How well does the Vector Dominance Model work?

It works wonderfully well for the pion form factor. This is shown in Fig. 2, where we compare the VDM calculation of Herrmann *et al.* [6] to data taken both in the time-like and space-like regions [7]. In this case, the form factor is dominated by the conversion of the virtual meson into a $\rho$-meson (Fig. 3). The $\rho$-meson shape translates directly into the structure of the pion electromagnetic form factor in the time-like region (upper Fig. 2) and describes well also the space-like region (lower Fig. 2). The root-mean-square radius of the pion obtained by Fourier transforming Eq. (4) is in very good agreement with the measured value of $\sim 0.65$ fm. In other words, the electromagnetic form factor of the pion is entirely given by the conversion of the photon into a $\rho$-meson coupled to a point-like pion.

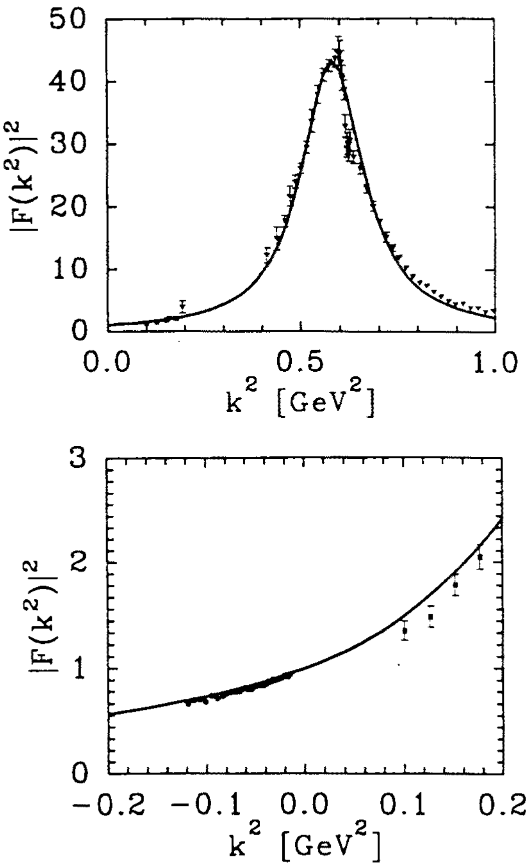


Fig. 2. Vector Dominance Model calculation [6] of the pion electromagnetic form factor in the time-like region (upper figure) and in the low $k^2$ space-like and time-like regions (lower figure). The data are from Ref.[7].

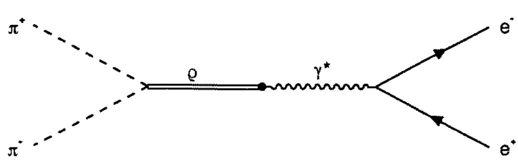


Fig. 3. $\rho$ Dominance Model of the pion electromagnetic form factor.

The Vector Dominance Model is also very successful in explaining the electromagnetic structure of the $\eta$-meson. The data are not as direct as for the pion. They use the two (real or virtual) photon decay of the $\eta$-meson [5]. Of particular interest is the Dalitz decay of the $\eta$-meson, *i.e.* its decay into a real photon and a virtual photon materializing into a lepton pair, $\eta \to \gamma\, e^+e^-$ and $\eta \to \gamma\, \mu^+\mu^-$. Assuming Vector Dominance for the virtual photon coupling (Fig. 4), the $q^2$-dependence of the transition form factor $\eta \to \gamma\, \mu^+ \mu^-$ is very well reproduced [8]. Another interesting decay of the $\eta$-meson is the $\eta \to \mu^+ \mu^-$ transition. Pseudoscalar mesons, like $\eta$'s, go into lepton pairs by decaying into 2 photons which couple to a lepton line (Fig. 5) [8]. A recent accurate measurement of this branching ratio at SATURNE [9] has given a value in very good agreement with the VDM description of the coupling of the $\eta$-meson to 2 virtual photons.

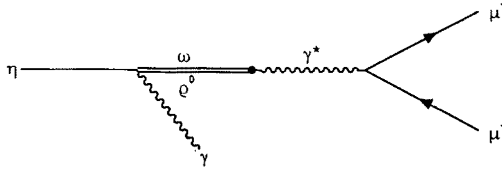


Fig. 4. Vector Dominance Model of the $\eta$ Dalitz decay form factor.

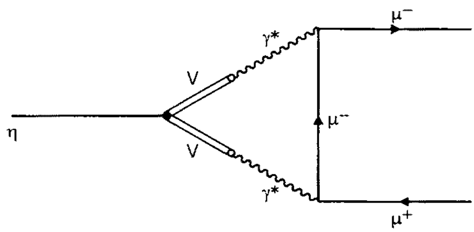


Fig. 5. Vector Dominance Model of the dileptonic decay of the $\eta$-meson.

Very poor data for the $\eta' \to \gamma\, \mu^+ \mu^-$ form factor suggest that it can also be understood in terms of the Vector Dominance Model [8].

The Vector Dominance Model in its simple form discussed above fails to reproduce other measured electromagnetic form factors. In the time-like region, the $\omega$ Dalitz decay form factor, corresponding to the $\omega \to \pi^0\, \mu^+ \mu^-$ process, is largely underestimated in the $q^2 \simeq 0.3$ - $0.4$ GeV$^2$ region (Fig. 6) [8] by the $\rho$ Dominance Model of the virtual photon materializing into the $\mu^+ \mu^-$ pair (Fig. 7). This implies that the electromagnetic "size" of the $\omega\pi^0$ transition vertex is larger than predicted by VDM, so that the $\omega\rho^0\pi^0$ interaction appears extended rather than point-like. This $\omega\rho^0\pi^0$ vertex happens to play a major role in many processes leading to vector meson production and therefore better data than those of Fig. 6 are badly needed.

For baryons, form factors in the time-like region, which are the most sensitive tests of Eq. (4) because they show the vector meson resonance structure, are not available in the kinematic region of interest ($q^2 \leq 1\text{GeV}^2/c^2$). Of particular relevance for the study of lepton pairs emitted in nuclear reactions are the nucleon electromagnetic time-like form factors and the $\Delta$ Dalitz decay form factor ($\Delta \to N\, e^+ e^-$). Knowledge on these processes

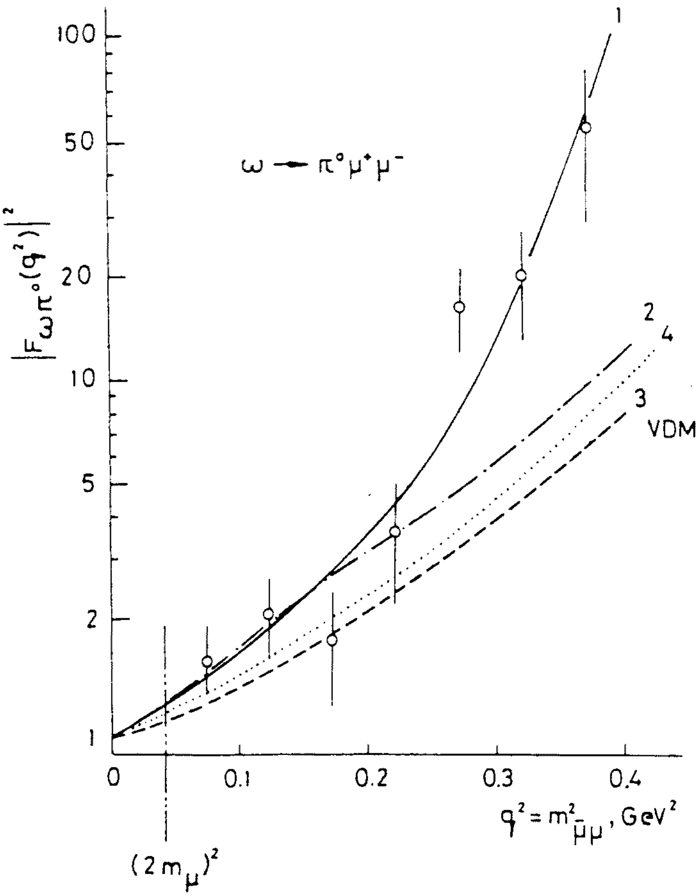


Fig. 6. $\omega$ Dalitz decay form factor [8].

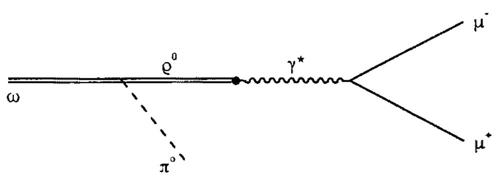


Fig. 7. Vector Dominance Model of the $\omega$ Dalitz decay form factor.

would open a sector of photon-hadron interactions which is at present completely unknown.

Baryon electromagnetic form factors have been measured extensively in the space-like region [10]. For the proton, the decrease of the electric form factor (-1 $\mathrm{GeV}^2 < q^2 < 0$) is very well fitted by a dipole form,

$$F_p{}^E(q^2) = \left[\frac{1}{1 - q^2/(0.71\mathrm{GeV}^2)}\right]^2 . \tag{5}$$

This is clearly different from the expected Vector Dominance slope, given by Eq. (4) with $\Gamma(q^2)=0$. It is actually about the square of that expression. As in the case of the $\omega$-meson, this can be interpreted by generalizing VDM and assuming that intermediate vector mesons couple to an extended vector meson source rather than to a point-like nucleon [11, 12]. The size of this source is of the order of 0.4-0.5 fm [12].

From this brief discussion, it is clear that a lot remains to be understood about the coupling of $|q^2| \leq 1\mathrm{GeV}^2/c^2$ photons with hadrons. The kinematic region most sensitive to the role of the mixing of virtual photons with vector mesons in this coupling is the *time-like* region. It is therefore very important to have good data on electromagnetic form factors in this regime. A major step in the quality of those data is expected from the combination of the pion beam and the HADES large acceptance $e^+e^-$ detector [13] at GSI.

The planned pion beam will make it possible to produce secondary sources of mesons, pseudoscalar $(\eta, \eta')$ or vector $(\rho, \omega, \phi)$. The HADES dilepton detector can then be used to study the decays of these mesons involving $e^+e^-$ pairs and obtain accurate data on Dalitz decay form factors.

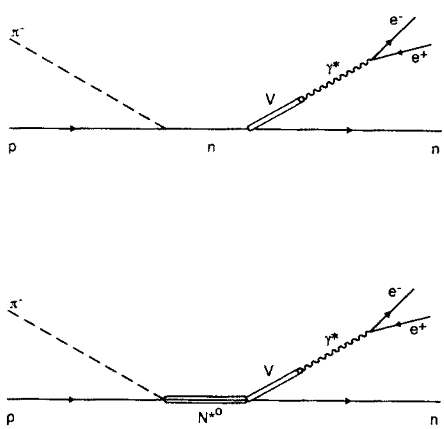


Fig. 8. Contributions to the $\pi^- p \to ne^+e^-$ process reflecting the neutron (upper figure) and the baryon resonance Dalitz decay (lower figure) form factors.

HADES, combined to the neutron detector LAND, will also provide access to the presently unknown baryon form factors in the time-like region. The basic reaction is the $\pi^- p \to ne^+e^-$ process. Baryon time-like form factors can be derived by isolating the contribution from graphs as those shown in Fig. 8 for the neutron and baryon resonance Dalitz decay form factors. As emphasized before, these measurements would provide the first data on photon-baryon interactions in the $0 < q^2 < 1\text{GeV}^2/c^2$ regime.

Theoretical developments in the understanding of the coupling of virtual photons to hadrons go in the directions of studying vertex corrections in effective hadronic theories involving vector mesons and establishing links between the Vector Dominance Model and Quantum Chromodynamics (QCD) [14].

## 4. Vector mesons in the nuclear medium

The main motivation for studying the properties of vector mesons in the nuclear medium comes from chiral symmetry, an approximate symmetry of QCD which plays a major role in hadron dynamics [15]. QCD is chirally invariant in the limit where quarks have zero masses. This is a very good approximation for u and d quarks, which have masses of a few MeV, a more questionable approximation for the s quark expected to have a mass of $\sim$ 150 MeV. Chiral invariance reflects the separate conservation of the helicity of left- and right-handed quarks, which evolve independently in the limit where they are massless. The associated symmetry group is, therefore, $\text{SU}(2)_L \times \text{SU}(2)_R$ (u and d quarks).

Chiral symmetry is *explicitly* broken by the small quark masses. It is also *spontaneously* broken [15]. This means that the symmetry does not manifest itself by parity multiplets in hadron spectra but rather by the presence of low-energy excitations (or Goldstone bosons), the pions. In the chiral limit ($m_u=m_d=0$), the pions would be massless. Their non-zero mass ($\sim$ 140 MeV) is generated by the explicit breaking of chiral symmetry. As a consequence of the spontaneous breaking of chiral symmetry, the QCD vacuum has a complicated structure. It is characterized by a non-zero expectation value $\langle\overline{q}q\rangle$, the quark condensate, estimated to be [15]

$$\langle\overline{q}q\rangle \simeq -[(230 \pm 25)\text{MeV}]^3 \simeq -(1.5 \pm 0.7)\text{fm}^{-3}\,, \tag{6}$$

for both u and d quarks. This is a property of the QCD vacuum at zero density and temperature. When the density or temperature increases, this expectation value goes down and would reach zero at the critical density ($\rho_c \simeq 3\rho_0$) or temperature ($T_c \simeq 150$ MeV) if chiral symmetry was not explicitly broken by the finite quark masses; the QCD vacuum evolves towards a normal vacuum and the pions decouple [15]. Observing this non-perturbative property of QCD, called *chiral symmetry restoration*, is a most interesting challenge.

The behaviour of the quark condensate as function of density and temperature, obtained in the Nambu–Jona–Lasinio model [16], is displayed in Fig. 9 and suggests the experimental conditions appropriate to the observation of chiral symmetry restoration. The right curve of Fig. 9 indicates that the decrease of $\langle\bar{q}q\rangle$ as function of density is linear and of the order of 25% at nuclear matter density ($\rho_0 = 0.17 N fm^{-3}$). Effects related to chiral symmetry restoration should therefore be already observable in nuclei. Relativistic heavy ion collisions ($E/A \simeq 1 - 2$GeV), in which matter around (2-3)$\rho_0$ can be produced, should be most useful to study this phenomenon. The left curve of Fig. 9 shows that the decrease of $\langle\bar{q}q\rangle$ with temperature happens suddenly, very close to the critical temperature, indicating that ultra-relativistic heavy ion collisions should be the relevant approach to study the behaviour of $\langle\bar{q}q\rangle$ at high $T$. Recent QCD lattice calculations [17] confirm the result shown in the left part of Fig.9.

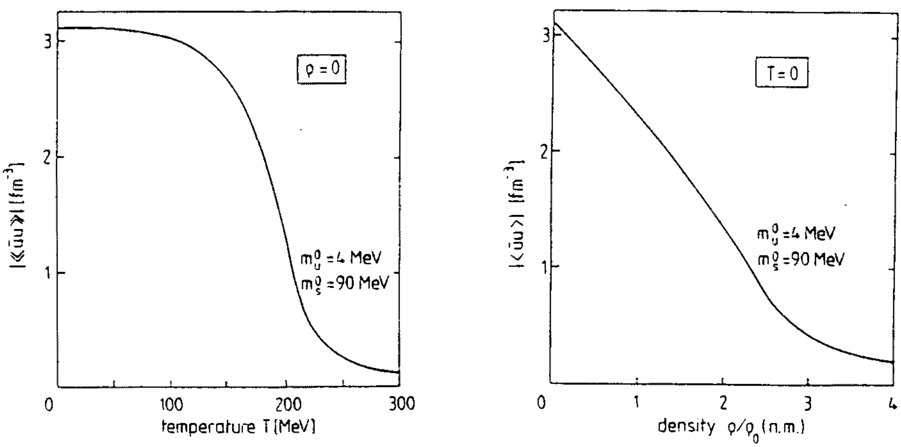


Fig. 9. Temperature and density dependence of the (light) quark condensate in the Nambu–Jona–Lasinio model [16].

The main problem is to find quantities which can be measured and reflect the decrease of $\langle\bar{q}q\rangle$ with increasing density or temperature.

Brown and Rho [3] suggested that vector meson masses are such quantities. Using symmetry properties of QCD in effective lagrangian theories, they showed that vector meson masses scale like the cubic root of the quark condensate,

$$\frac{M_\rho^*(\rho)}{M_\rho(0)} = \frac{M_\omega^*(\rho)}{M_\omega(0)} = \left(\frac{\langle\bar{q}q\rangle_\rho}{\langle\bar{q}q\rangle_0}\right)^{1/3} . \tag{7}$$

This would imply that the $\rho$- and $\omega$-meson masses have decreased by $\sim 100$ MeV at $\rho = \rho_0$, an effect expected to be observable in nuclei. This link between the $\rho$ mass and the quark condensate is illustrated in Fig. 10 (from Ref. [18]). The $\rho$ mass is generated by the coupling of the $\rho$-meson to the quark condensate through a scalar field.

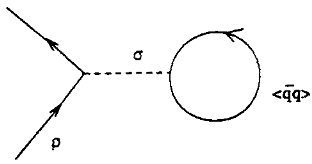


Fig. 10. Generation of the $\rho$-meson mass through the scalar coupling to the quark condensate [18].

Decreasing vector meson masses with increasing densities are also obtained by extending the techniques of QCD sum rules to nuclear matter [19, 20]. The limitations of this approach are discussed in Ref. [21].

## 5. Dileptonic studies of vector meson properties in nuclei

As a consequence of the above discussion, it would be very desirable to measure vector meson masses in nuclei. In order to observe in-medium properties, one must study vector mesons which are produced and decay in nuclei and reconstruct their invariant mass from the decay products. The candidates for such measurements are necessarily broad mesons, so that their mean free path is shorter than the nuclear size. This is clearly the case for the $\rho$-meson ($c\tau_\rho = 1.3$ fm in free space), while the $\omega$- and $\phi$-mesons appear too narrow ($c\tau_\omega = 23.4$ fm and $c\tau_\phi = 44.4$ fm in free space), unless they are very much broadened in the medium. It is also important that the $\rho$-mesons be produced close to threshold, so that their formation time and lifetime do not get multiplied by a large Lorentz factor. As discussed in the introduction, the best way of studying vector mesons in nuclei is to measure their dileptonic decay ($e^+e^-$ in particular), which is not distorted by strong interactions and allows invariant mass reconstruction. This is in contrast to the $2\pi$ decay of $\rho$-mesons, which produce pions in a kinematic regime where they reinteract strongly with nucleons due to the $\Delta$ dominated p-wave $\pi$N interaction.

A nice way of producing vector mesons inside nuclei is through photoproduction experiments. Photoproduction from nuclear targets of vector mesons observed by dielectron pairs are proposed at CEBAF, using the CLAS detector [22, 23]. The reaction of interest is $A(\gamma, e^+e^-)$, with photon energies between $\sim$1.2 and 2 GeV and invariant $e^+e^-$ masses between 600 and 900 MeV. Both $\rho$- and $\omega$-mesons are produced in this reaction and their contribution to the dielectron spectrum can be isolated [24].

Such processes have been studied before at higher photon energies. In particular, there are very good data on the Be($\gamma, e^+e^-$)Be reaction at $E_\gamma$ = 5.1 GeV [24]. The Be nucleus is very small and the Lorentz factor corresponding to the kinematics of the produced vector mesons is 6.7, so that the $e^+e^-$ pairs measured at 5.1 GeV come dominantly from vector mesons decaying in free space because of time dilatation. Consequently, they do not carry any information on the in-medium behaviour of vector mesons. The shape of the $e^+e^-$ pair invariant mass spectrum coming from $\rho$ and $\omega$ production is very interesting though. It is shown in Fig. 11. It is a typical interference pattern, which result from the fact that the $\rho(770)$ and the $\omega(782)$ have similar masses. The peak reflects the $\omega$ contribution; the quantum interference between $\rho$- and $\omega$-mesons is constructive on the left side of the peak and destructive on its right side [25].

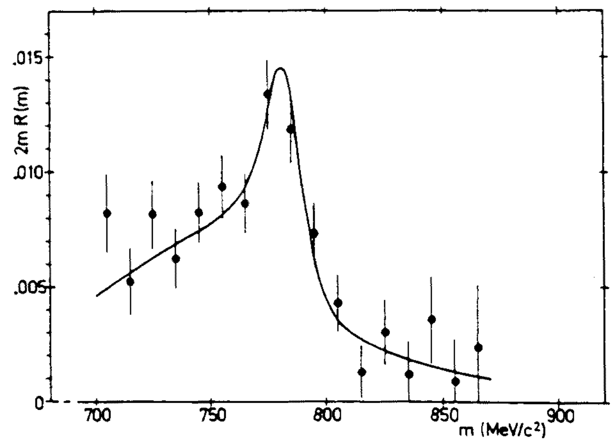


Fig. 11. Invariant mass spectrum of $e^+e^-$ pairs associated to vector meson production in the $Be(\gamma, e^+e^-)Be$ reaction at $E_\gamma$=5.1 GeV [24].

If such curve was measured near threshold ($E_\gamma \lesssim$ 2 GeV) and the $\rho$ mass would decrease significantly, the interference would be largely destroyed [25], providing a very nice signature of a change of vector meson properties in nuclei (we assume that the $\omega$ decays mostly outside the target, where it has its free mass).

To interpret such data, it is of course necessary to have a good understanding of the photoproduction of vector mesons from the proton in that energy range. With this purpose in mind, we have derived a simple meson-exchange model of $\rho$ and $\omega$ photoproduction on the proton [25]. The contributions to the $\gamma p \to \rho p$ cross section allowed in the Born approximation are shown in Fig. 12. The $\sigma$-exchange dominates largely over the $\pi$-exchange because $f_\rho{}^2$ is larger than $f_\omega{}^2$ by about an order of magnitude

(Eqs. (2) and (3)). Using standard parameters for the $\sigma pp$ vertex, we adjusted the $\sigma\rho\rho$ coupling to reproduce the available data on the $\gamma p \to \rho p$ cross section below 2.5 GeV [26]. We found a large value of the coupling constant ($g^2_{\sigma\rho\rho}/4\pi$=12). However, the available data have large error bars and much better measurements are needed to discuss a detailed fit.

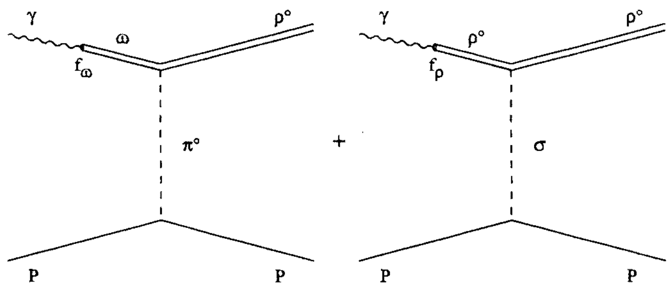


Fig. 12. $t$-channel processes contributing to $\gamma p \to \rho^0 p$ [25].

The dominance of the $\sigma$-exchange process in the $\gamma p \to \rho p$ cross section is a very important point because it makes it possible to derive from the analysis of this process the strength of the $\rho$N interaction (as can be seen from the right-hand side of Fig. 12). This knowledge is necessary to understand final state effects when $\rho$-mesons are produced in a nuclear environment. Work is in progress to go beyond the Born approximation in the $\gamma p \to \rho^0 p$ process and to gain a dynamical understanding of the scalar exchange parameters [27].

Vector mesons can also be produced in nuclei with incident protons or pions, even though they are less penetrating probes than photons. Dilepton data from p+Be collisions from 1.05 until 4.9 GeV have been obtained at the BEVALAC by the DLS Collaboration [28]. Because of the small radius of Be and of the large error bars in the $e^+e^-$ invariant mass spectrum in the vector meson mass region, those data are unfortunately not suited to discuss in-medium vector meson masses. An interesting possibility [29] is to use the planned pion beam at GSI to study recoilless vector meson production in nuclei, measured in the $e^+e^-$ channel with the HADES detector.

Two issues need to be addressed in connection with the interpretation of dilepton data on vector meson masses in nuclei. The first issue is the density dependence of vector meson widths. This is particularly important for the $\rho$-meson [6]. As a consequence of its large width, the position of the peak of the $\rho$-meson spectrum plotted as function of the invariant mass of the electron pair will not appear at the actual $\rho$ mass but lower. This is because the cross section is proportional to $[(m^2\text{-}M_\rho^2)^2+M_\rho^2\Gamma_\rho^2(m)]^{-1}$, where m is the invariant mass of the $e^+e^-$ pair. For the free width ($\Gamma_\rho$=151.5 MeV), the peak position is lower than the $\rho$ mass by $\sim$20 MeV. If the width is doubled in nuclei, as suggested in Ref. [6] for $\rho = \rho_0$, it is lower by $\sim$65 MeV. This effect needs obviously to be included in any analysis of data. A second problem at high density is the possible mixing of $\rho$-mesons with nuclear excitations of similar quantum numbers. The mixing of the $\rho$-meson to $\pi\pi$ states does not seem to affect its mass very much, at least for $\rho \simeq \rho_0$ [6]. The $\rho$-meson could also mix in matter with $\Delta$-hole states, or more generally $N^*$-hole states. This mixing must be studied.

## 6. Dileptons from heavy ion collisions

The main purpose of studying dileptons from heavy ion collisions is to get as direct an information as possible on the behaviour of hadronic matter at very high baryon density and temperature.

One should distinguish two regimes: relativistic collisions (E/A$\simeq$1-2 GeV), where densities of the order of (2-3)$\rho_0$ and rather low temperatures are prevailing, and ultra-relativistic collisions (E/A$\geq$100 GeV), where very high temperatures, of the order or larger than the critical temperature for chiral symmetry restoration, are expected to be reached.

We begin by discussing the high density-low temperature regime. Dilepton measurements in relativistic heavy ion collisions were first realized at the BEVALAC by the DLS Collaboration [30] and will be pursued with much increased acceptance and mass resolution at GSI by the HADES Collaboration [13].

The interpretation of these data is not simple. It depends on the thermodynamic conditions and hadronic composition of the system formed in the collision process, on the in-medium properties (mass and width) of the hadrons present in that system and on the decay form factors of these hadrons into $e^+e^-$ pairs inside and outside the reaction zone. All these ingredients have uncertainties, so that the understanding of dilepton spectra from heavy ion collisions is closely linked to resolving the problems discussed earlier in this lecture, such as the behaviour of hadron form factors in the time-like region and the in-medium properties of vector mesons at $\rho = \rho_0$.

Some results have emerged from theoretical studies based on transport equations of the Boltzmann–Uehling–Uhlenbeck type [31].

One interesting result is that dilepton production in the $\rho - \omega$ mass region appears dominated by $\pi^+\pi^-$ annihilation [31]. This is shown in Fig. 13 (dotted curve) [32]. The $\pi^+\pi^- \rightarrow e^+e^-$ annihilation process is nothing but the pion form factor of Fig. 3, which depends very much on the $\rho$-meson mass (Eq. (4)). If the $\rho$-mass changes in the medium, it should be substantially modified. This was shown for example by Li and Ko [33]

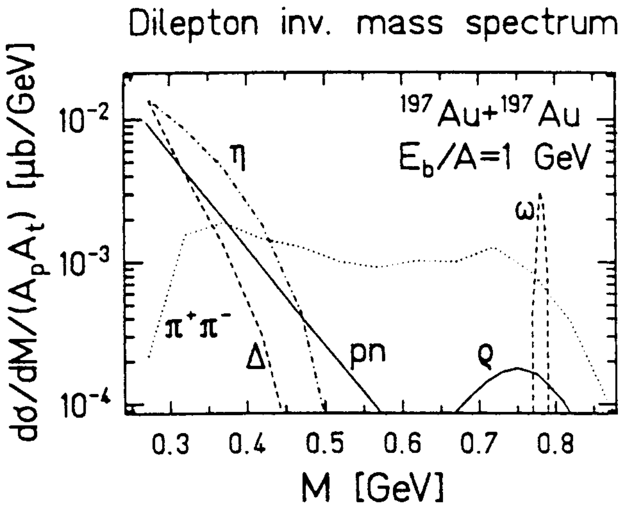


Fig. 13. Dilepton invariant mass spectrum in $^{197}$Au+$^{197}$Au collisions at 1 GeV per nucleon [32]. The curves marked $\rho$ and $\omega$ corresponds to $\rho \to e^+e^-$ and $\omega \to e^+e^-$. The curves marked $\pi^+\pi^-$, $\eta$, $\Delta$ and pn show the contributions from the $\pi^+\pi^-$ annihilation, the $\eta$ and $\Delta$ Dalitz decays and the pn bremstrahlung respectively (see text).

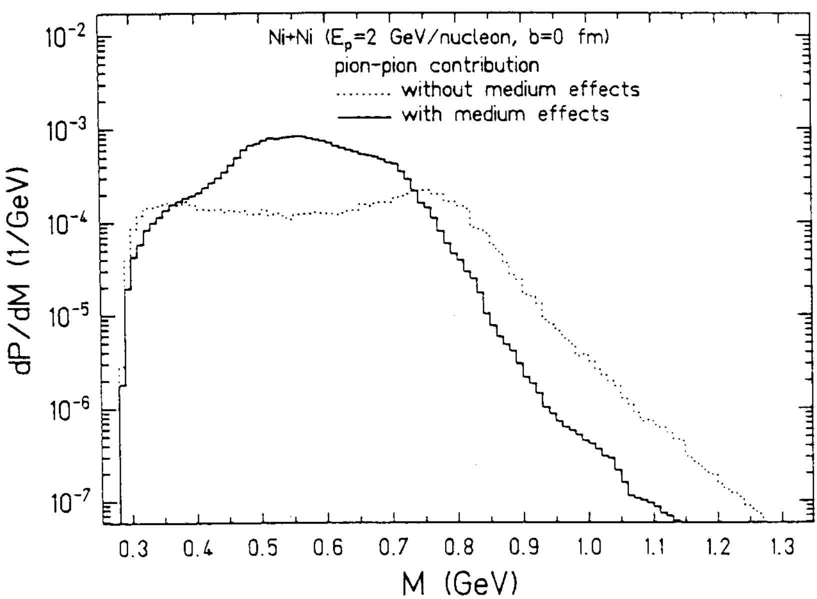


Fig. 14. Calculated spectrum of dielectrons produced in $\pi^+\pi^-$ annihilation in a central Ni+Ni collision at 2 GeV per nucleon with free (dotted line) and in-medium (full line) $\rho$ mass [33].

and is illustrated in Fig. 14. The dotted line corresponds to a calculation of the spectrum of dielectrons produced in $\pi^+\pi^-$ annihilation in a central Ni+Ni collision at 2 GeV per nucleon with the free $\rho$ mass. The enhancement around the $\rho$ mass is visible. If now the $\rho$ mass changes according to Eq. (7), the full line shows a large shift of the strength towards lower dilepton invariant masses. The BEVALAC data [30], which are uncertain by about an order of magnitude in the $\rho$ mass region, do not allow to draw any conclusion.

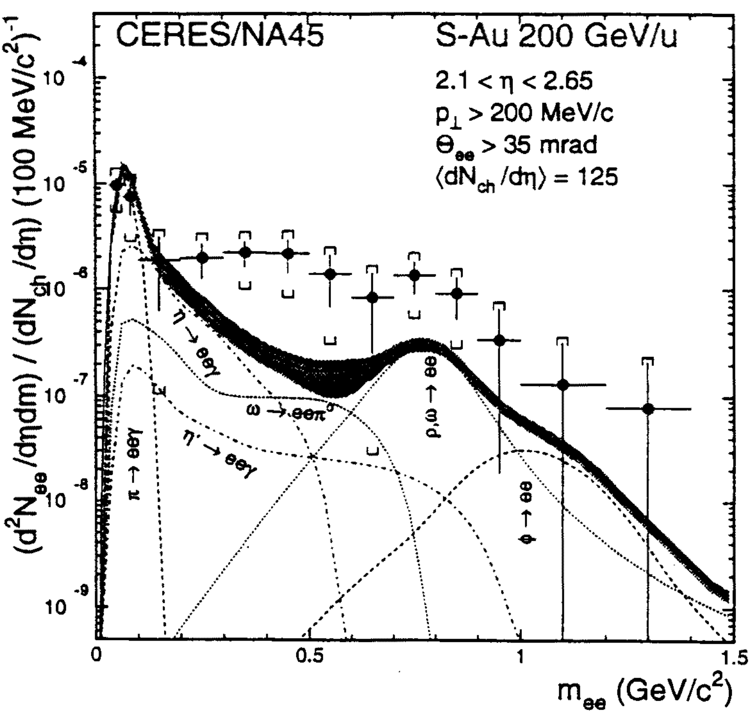


Fig. 15. Mass spectrum of $e^+e^-$ pairs measured in S+Au collisions at 200 GeV per nucleon together with the contributions of hadron decays. The shaded area indicates the systematic errors on the summed contributions [4].

As can be seen from Fig. 13, other processes play a role in producing dileptons in heavy ion collisions. They are mainly the $\eta$ Dalitz of Fig.4, the $\Delta$ Dalitz decay mentioned in Section 3, the $\rho$ and $\omega$ dilepton decays and the proton-neutron bremsstrahlung in the time-like region, $pn \to pne^+e^-$. The relative importance of these processes depends on the incident energy.

We mention now very interesting data obtained in ultra-relativistic heavy ion collisions at CERN by the CERES Collaboration [4], which could be very closely related to the physics discussed in this lecture. Dielectrons of invariant masses m<1.5 GeV have been measured in p+Be and p+Au collisions at 450 GeV and S+Au collisions at 200 GeV per nucleon at central rapidities. In the case of proton induced reactions, the dielectron spectra can be understood as resulting from hadron decays. On the contrary, in the S+Au reaction, the number of electron pairs produced in the invariant mass range 0.2<m<1.5 GeV is about 5 times larger than what is expected from hadron decays. This is shown in Fig.15. The range of invariant masses where this excess is most significant indicates that it could be due to $\pi^+\pi^-$ annihilation and the fact that the effect appears largest for 0.3<m<0.6 GeV suggests that the pion form factor could peak at a lower mass than the $\rho$-meson mass when the annihilation process takes place in a high temperature environment. These data provide therefore a very strong encouragement to look for medium effects in dilepton production from nuclei and nuclear collisions.

## 7. Conclusion

The coupling of dileptons to time-like photons and vector mesons makes them unique probes of vector degrees of freedom in free space and in the nuclear medium.

We have emphasized the open questions of this field. Of basic importance to make progress are accurate measurements of meson Dalitz decays and the study of the interaction of time-like photons with baryons. Good data on the photoproduction and electroproduction of vector mesons from proton targets are important to have constraints on the vector meson-nucleon interaction that enters all in-medium calculations. On the theoretical side, more accurate models of hadron form factors based both on effective hadronic field theories and QCD are needed. The in-medium mass of vector mesons is a very challenging question because of the suggestion that they could be order parameters for chiral symmetry restoration. The behaviour of vector mesons at high baryon density and temperature can but be studied by steps. Dileptonic decays of vector mesons produced in nuclei by photons, protons or pions of a few GeV offer the possibility of learning about their properties at $\rho \leq \rho_0$. The results of these studies will lead the way to extrapolations at higher densities, as those achieved in relativistic heavy ion collisions. Recent data obtained at ultra-relativistic energies suggest that in-medium hadronic physics produces indeed large effects in dilepton spectra for invariant masses $\leq$ 1 GeV.

The author thanks the organizers of the XXIV Mazurian Lakes Summer School of Physics for inviting her and offering her a first opportunity to visit Poland. She is very much indebted to Bengt Friman for work done in collaboration, countless discussions and shared enthusiasm about vector meson and dilepton physics. She acknowledges the hospitality of GSI which makes this collaboration possible and gives her the opportunity of frequent interactions with the HADES Collaboration.

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