Charm and leptons
P. Crochet\textsuperscript{a} *

\textsuperscript{a}Laboratoire de Physique Corpusculaire
CNRS/IN2P3 and Université Blaise Pascal
F-63000 Clermont-Ferrand, France

The present knowledge on charm and leptons is reviewed including the topics discussed at this conference and the progress made since the last Quark Matter conference. Special emphasis is placed on $J/\psi$ production at the SPS which is one of the highlights in the field.

1. Introduction

Observables related to charm and leptons are of great relevance in heavy ion collisions considering the significant information that they have revealed over the last years. The low mass dielectron yield measured by the CERES collaboration has provided evidence for in-medium effects on the $\rho$ meson. The $J/\psi$ suppression pattern observed by the NA50 collaboration is believed to be an important signature of the QGP. The intermediate mass dimuon excess in A-A reactions at SPS has been first attributed to an increase of the open charm cross-section. At the beginning of this year, the first measurement of the open charm cross-section in heavy ion collisions has been carried-out at RHIC by the PHENIX collaboration. On the other hand, the actual mechanism for charmonium production in heavy ion reactions is a subject of intensive current debate. Indeed, the new scenarios which have been recently proposed differ totally from the standard approach in their predictions. At RHIC they imply a significantly larger $J/\psi$ yield than that resulting from the standard suppression scenario. This makes the first $J/\psi$ measurements from PHENIX of crucial importance.

2. Low mass dileptons at SPS

Studies of low mass dielectrons at the SPS continue to attract a great interest since the observation of an excess beyond the expected sources in S-U reactions at 200 AGeV \cite{1} and in Pb-Au reactions at 158 AGeV \cite{2}. The enhancement is located in the invariant mass range $0.2 < m < 0.7$ GeV/$c^2$. It is found to be more pronounced at low $p_t$ and to increase with centrality. The final analysis of the 40 AGeV Pb-Au data presented at this conference \cite{3} confirms the preliminary results reported at the last Quark Matter conference \cite{4}: the data taken at 40 AGeV exhibit an even larger enhancement ($5.1 \pm 1.3$(stat) $\pm 1.0$(syst)) than at 158 AGeV ($2.9 \pm 0.3$(stat) $\pm 0.6$(syst)). This is probably

\textsuperscript{*}crochet@clermont.in2p3.fr
due to the maximum baryonic density reached in Pb-Au collisions at the lower beam energy. Note that, within errors, the measured dielectron yield is, in the considered invariant mass range, similar at both beam energies such that the larger excess observed at 40 AGeV actually results from a lower magnitude of the sum of known hadronic decay sources. The enhancement can be well accounted for by considering reduction in mass or broadening in width of the $\rho$ meson in the hot and dense medium (see [5] for a review and [6] for a recent update). Unfortunately, the present experimental resolution does not allow to disentangle the two scenarios (this might be improved with the analysis of the data taken in 2000). Another approach, recently proposed, is based on dileptons from a simple parameterization of a thermal source [7]. This approach is very successful in describing also the intermediate mass dilepton yield and the direct photons at SPS (see below). The derived space-time averaged temperature is 170(145) MeV at 158(40) AGeV.

It is interesting to note that the temperature at 158 AGeV coincide with the expected temperature of the phase transition. Its maximum is located at 210 MeV suggesting that the system originates from the deconfined region [7].

3. Intermediate mass dileptons at SPS

In the intermediate mass range (IMR, $1.5 < m < 2.5$ GeV/$c^2$), like in the case of the low mass region, an excess of dileptons is seen compared to known sources in A-A reactions. This has been observed by the HELIOS/3 [8] and NA50 [9] collaborations. An updated analysis was presented at the last Quark Matter conference [10]. The enhancement is found to increase linearly with $N_{\text{part}}$ and reaches a factor $\sim 2.1$ for the most central Pb-Pb events. Surprisingly, the kinematical distributions of the dimuon excess are compatible with those expected from open charm decay [9]. These findings have triggered a lot of theoretical activities with various interpretations: open charm enhancement [11], $D$ meson final state rescattering [12], secondary hadron production [13], secondary Drell-Yan production [14], $\eta_c$ production [15], thermal dilepton production [16], secondary meson-baryon interactions [18], in-medium Drell-Yan production [19]. Some of the proposed scenarios fail in reproducing the kinematical distributions of the excess, some fail in its centrality dependence and some underpredict its magnitude. The most successful description of the data has been achieved by means of thermal dileptons [16] (see also [17]). Indeed, with a common thermal source one can simultaneously reproduce the low mass dielectron yield from CERES, the IMR dimuons from NA50 and HELIOS/3 as well as the direct photons from WA98 [7]. However, it should be mentioned that a recent investigation of the centrality dependence of the IMR dimuon excess leads to a source temperature which is significantly larger than that estimated from central events only [20]. This could leave room for a partial contribution from one or some of the other effects listed above.

One should finally note that, from the experimental point of view, this kind of analysis requires a thorough understanding of the combinatorial background. This is because, in contrast to narrow resonances, the present broad signal does not clearly stick-out of the background. In particular, special attention should be paid to situations with a production asymmetry between positive and negative leptons and a large signal which will lead to an incorrect background subtraction and therefore to a biased extracted signal [21].
4. Open charm at RHIC

The first (indirect) measurement of the open charm cross-section in heavy ion collisions has been carried-out recently by the PHENIX collaboration via analysis of single electron spectra in Au-Au at $\sqrt{s} = 130$ GeV [22]. After subtracting all known sources from the total distribution the remaining electron spectra are, in the explored $p_t$ range, in good agreement with electron spectra from open charm decay as predicted using PYTHIA (tuned to reproduce existing hadron-nucleon data at lower beam energies and then extrapolated to Au-An at RHIC). The derived integrated cross-section is in good agreement with PYTHIA and consistent with pQCD NLO calculations. Therefore, in contrast to the SPS IMR dimuon data, there is no need for charm enhancement in order to explain the RHIC single electron spectra. However, because of the present large systematical errors, one cannot firmly exclude in-medium effects on charm production at RHIC. It was actually pointed-out at this conference that the small differences at high $p_t$ between the minimum-bias spectrum and the central spectrum could be explained by considering energy loss of charm quarks [23].

The analysis was repeated for the 200 GeV data [24]. Here, the determination of the background was done in a completely different way, namely by using a photon converter instead of the cocktail technique which was used for the 130 GeV data. Again, the data agree well with the expectations from PYTHIA. This holds true for several centrality bins such that, here again, not much room is left for large in-medium effects. However, it is clear that the safest way to make a definite statement about in-medium effects on open charm at RHIC is to compare the Au-Au data to the p-p data. This is hopefully going to be done soon [24].

Another interesting perspective, with the coming high luminosity runs, is the independent measurement of the open charm cross-section from the dielectron continuum above the $\phi$ meson. All these measurements could provide precious information on open bottom by looking at high $p_t$ and high invariant mass. They would be greatly improved by means of high resolution vertex detectors owing to the large $c\tau$ of open charm and open bottom hadrons. Note finally that non-direct measurements of open charm (bottom) from semi-leptonic decays bring limited information only. Direct measurements of open charm hadrons remain an important goal of the heavy quark physics program at RHIC.

5. Charmonium at SPS

After many years of intensive experimental and theoretical investigations, charmonium production at SPS remains one of the hottest topic in the field (see [25] for reviews). This is because the observed behaviour of $J/\psi$ is believed to exhibit one of the most pronounced deviation with respect to pure conventional hadronic picture.

The so-called “$J/\psi$ anomalous suppression” has been observed by the NA50 collaboration with the data collected in 1996 and 1998. It manifests itself by a departure from the “normal” nuclear absorption when looking at the centrality dependence of the $(J/\psi)/(DY)$ ratio in Pb-Pb reactions [26, 27]. The ratio is obtained by means of either the standard method or the minimum-bias method. The centrality of the reactions is measured with the neutral transverse energy ($E_t$) and the Zero Degree Calorimeter energy ($E_{ZDC}$). A $\sim 20\%$ drop is observed at $E_t \sim 40$ GeV, followed by a decrease at $E_t \sim 100$ GeV (Tab. 1).
The NA50 collaboration interprets this pattern as an evidence for deconfinement. In this scenario, the drop results from the melting of $\chi_c$ and the decrease from the melting of $J/\psi$. This can be checked \cite{31} by comparing the energy densities derived from the data (Tab. 1) with the expected charmonia dissociation temperatures from recent studies based on the heavy quark potential from LQCD \cite{32}. The data agree with the predictions within $\sim 20\%$. This is a fairly good agreement considering the uncertainties in the way the energy density is derived from the data. Note however that these studies assume the $\chi_c$ decay branching ratio into $J/\psi$ in heavy ion reactions to be the same as in p-p.

Table 1
Location of the drop and the decrease with the transverse energy ($E_t$), the Zero Degree Calorimeter energy ($E_{ZDC}$), the path length through matter (L), the impact parameter (b), the number of participant nucleons ($N_{\text{part}}$) and the energy density ($\epsilon$). The values are from the data collected in 1996 and 1998 \cite{26, 27}.

|        | $E_t$ (GeV) | $E_{ZDC}$ (TeV) | L (fm) | b (fm) | $N_{\text{part}}$ | $\epsilon$ (GeV/fm$^3$) |
|--------|------------|----------------|--------|--------|-------------------|---------------------|
| drop   | 41         | 25             | 8      | 8      | 122               | 2.3                 |
| decrease | 100       | 9              | 9.3    | 3      | 334               | 3.1                 |

5.1. $(J/\psi)/(DY)$ in central Pb-Pb

The interpretation of the decrease as due to the melting of $J/\psi$ is not straightforward in a dynamical picture. Indeed, QGP models which assume two sharp thresholds corresponding to the successive meltings of $\chi_c$ and $J/\psi$ overpredict the data in the decrease (i.e. beyond $E_t = 100$ GeV) \cite{33}. In fact, it was realized that at $E_t = 100$ GeV the $E_t$ distribution exhibits the typical knee beyond which there is no further sensitivity to centrality and fluctuations set in \cite{34}. By taking into account these fluctuations, a perfect fit of the data is achieved over all the centrality range with either two thresholds or one gradual threshold \cite{34}. In other words, in the framework of QGP models, the decrease seen in the data cannot be non-ambiguously associated to the melting of $J/\psi$.

Furthermore, it has recently been pointed-out that the decrease may hide another effect which has strictly nothing to do with the QGP but which is related to the trigger of the NA50 spectrometer \cite{35}. An event which fulfills the $J/\psi$ trigger conditions should have, in average, a smaller $E_t$ than a minimum-bias event because a fraction of $E_t$ is taken away by the $J/\psi$. Therefore, in the minimum-bias analysis, the $(J/\psi)/(DY)$ ratio is biased because the $J/\psi$ yield is measured (under trigger conditions) whereas the Drell-Yan yield is calculated (without trigger conditions). It has been shown in \cite{35} that this effect leads to an extra depletion of the $(J/\psi)/(DY)_{\text{min-bias}}$ ratio in the $E_t$ range of the decrease. Consequently, with $E_t$ fluctuations and $E_t$ loss effects, the comover model provides a very good description of the data up to the most central events \cite{35}. This also holds true for other models based on different scenarios \cite{36, 37, 38} and would probably also hold true for former models which assume or not the formation of the QGP \cite{39}. In this context the decrease cannot be considered any longer as a valid point to disprove a model which would exhibit a saturation of the $(J/\psi)/(DY)$ ratio at high $E_t$. Note that the trigger $E_t$

\footnote{The fraction of $J/\psi$ from $\chi_c$ decay is $\sim 30\%$ in p-$\bar{p}$ at $\sqrt{s} = 1.8$ TeV \cite{29} and $\sim 32\%$ in p-A at $\sqrt{s} = 41.6$ GeV \cite{40}.}
loss effect can, in principle, be confirmed or disproved by taking Drell-Yan data at large $E_t$ and/or by measuring at RHIC the $J/\psi$ yield at the energy density corresponding to that of the decrease at the SPS.

5.2. $(J/\psi)/(DY)$ in peripheral Pb-Pb

At the time of the last Quark Matter conference, the $(J/\psi)/(DY)$ data at low $E_t$ were subject to different interpretations. Indeed, as it can be seen from Fig. 8 of [40], at low $E_t$, some models underpredict the data, some overpredict the data and some go through the data. On the other hand, the data points below $E_t = 30$ GeV are located above the nuclear absorption curve which means that they show less absorption than in p-A and S-U systems. The same feature is observed at large $E_{ZDC}$ [27] (i.e. for the same centrality class). This is difficult to understand in the QGP picture since the suppression should be “normal” below the (first) threshold. However, it was believed that, for these peripheral events, the data could be contaminated by beam-air interactions. In order to clarify the situation new data were taken in 2000 with the target placed in the vacuum to minimize off-target interactions. The software was also improved with new methods for rejection of pile-up events and identification of the interaction point. In parallel, more accurate measurements of p-A data were made in order to estimate with better precision the $J/\psi$ nuclear absorption cross-section. The updated value is $\sigma_{abs}^{J/\psi} = 4.4 \pm 0.5$ mb [41] (the former was $\sigma_{abs}^{J/\psi} = 6.4 \pm 0.8$ mb [42]).

Conclusion: It has been shown at this conference [43] that the published peripheral $(J/\psi)/(DY)$ data suffer from a systematical bias due to beam-air interactions (a $\sim 25\%$ effect at $E_t = 15$ GeV). It has been argued in [33] that the central $(J/\psi)/(DY)_{\text{min-bias}}$ data might be affected by a systematical bias due to trigger $E_t$ loss (a $\sim 20\%$ effect at $E_t = 120$ GeV). Very recently, it has been claimed that there might be systematical inconsistencies between the $E_t$ data and the $E_{ZDC}$ data for semi-central events [28]. As interpretations are often being drawn at a few percent level, it is extremely important that the data are carefully checked for systematical effects. In addition, more stringent tests of the models could certainly be achieved i) by studying simultaneously the centrality dependence of yields together with ratios and ii) by extending investigations to all available observables. The latter should include, in particular, the transverse momentum dependence of the suppression discussed below.

5.3. Transverse momentum dependence of the suppression

The $p_t$ dependence of the $J/\psi$ suppression was early considered to be the golden observable to prove the existence of the QGP. Traditionally the data are presented in terms of the centrality dependence of the $<p_t^2>$ of $J/\psi$ in order to provide evidence for the $p_t$ broadening effect due to initial state parton scattering which is expected in absence of QGP. In a deconfined medium, it was first believed that one should observe additional $p_t$ broadening with increasing centrality [15]. This is because, due to the resonance for-
mation time and screening effects, only high $p_t$ $J/\psi$ could escape the medium whereas low $p_t$ $J/\psi$ would melt. Later on, it was claimed [46] that an opposite effect should actually happen, namely $<p_t^2>$ flattening or even decreasing. The reason is that high $p_t$ $J/\psi$ are those which travel through the largest amount of matter and therefore are those which come from the center of the reaction. Since the local density is the highest in the central region these high $p_t$ $J/\psi$ should be the most QGP suppressed. On the other hand, comovers are expected to produce a weak $<p_t^2>$ flattening [47, 48].

The NA50 Pb-Pb data [49] are shown in Fig. 1 (see [50] for the data taken in 2000 and [51] for the S-U data at 200 AGeV). They show a smooth increase of $<p_t^2>$ with centrality and a saturation when approaching mid-central reactions. It is astounding to note that the data do not show any significant sign for onsets, steps or drops and it would be remarkable that the two QGP effects mentioned above would exactly cancel each other. Even more striking is the outcome of the comparison with the theory, since the only model which significantly misses the data is the QGP model (first noticed in [52]). This means that something is inconsistent when looking simultaneously at $(J/\psi)/(DY)$ and at $<p_t^2>$ of $J/\psi$. It is therefore of crucial importance to further investigate these data carefully. To this respect, it is also important to stress that one would surely learn much more from the spectra themselves instead of limiting the study to mean values.

Another interesting aspect of the centrality dependence of the $J/\psi$ $p_t$ spectra has been presented at this conference [50]. The $J/\psi$ inverse slope parameters for p-A, S-U and non-central Pb-Pb reactions fall on a common straight line when plotted as a function of the energy density. However, for the most-central Pb-Pb events one observes a flattening of the apparent temperatures. This could indicate a change in the expansion of the system.

5.4. Non-direct charmonium production

Charmonium production from statistical hadronization has been extensively discussed in a parallel session at this conference. This production mechanism is based on a twofold

\[\text{As illustrated in [53], the fact that a model gets the mean of a distribution right does not necessarily mean that the full distribution is understood.}\]
observation [54]. First, because of cross-section considerations, the treatment of charmed hadrons in a standard thermal model cannot be easily justified. Secondly, in central Pb-Pb reactions at SPS the measured $\psi'/J_\psi$ ratio is $\sim 4\%$ as predicted by the thermal model. This led to a new scenario for charmonium production [54]: i) all $c\bar{c}$ pairs are produced in the early stage via hard scattering; ii) all charm hadrons are produced statistically at the hadronization. The underlying picture is that the charm hadrons either do not form in the early stages or are fully suppressed in the QGP. This scenario can be implemented in the framework of a thermal model by using the formalism described in [54,55,56] where one includes a charm enhancement factor in order to match the multiplicity of directly produced $c\bar{c}$ pairs. Since the open charm cross-section has not yet been measured at SPS, it is taken from the predictions of pQCD.

This approach has been studied in detail in the two last years [54,55,56,57,36,60,61,37]. As shown in [56] the measured $J/\psi$ yield versus $N_{\text{part}}$ in Pb-Pb is qualitatively consistent with the centrality dependence of the nuclear overlap function. In order to reproduce the yields, one needs to enhance the charm cross-section in the model with respect to the predictions from pQCD. This extra charm enhancement amounts to a factor $\sim 2$. This is surprisingly similar to the open charm-like enhancement needed in order to account for the excess of the IMR dimuon yield observed in central Pb-Pb events at SPS [10]. Another realization of the statistical hadronization model also provides a very good fit of the $E_t$ dependence of the $(J/\psi)/(D\gamma)$ ratio, albeit with a larger enhancement factor [57,36].

An additional experimental indication for statistical hadronization of charmonium at SPS has been put forward in [58] (see [59] for the model predictions at RHIC): The $m_t$ spectra of $\Omega^\pm$ from WA97 and $J/\psi$ and $\psi'$ from NA50 can be simultaneously described in a hydrodynamical picture of hadronizing QGP with $T = T_c = 170$ MeV and $\bar{v} = 0.2$ ($\bar{v}$ is the average transverse flow velocity). This supports the idea of charmonium formation and kinetic freeze-out at the hadronization.

The statistical hadronization model can also be used to predict charmonium yield at RHIC [50,59]. At RHIC, depending on the beam energy, the total multiplicity of (directly produced) $c\bar{c}$ pairs is expected to be smaller than one in peripheral reactions and larger than one in central reactions. Because the statistical hadronization process is strongly correlated to the multiplicity of the $c\bar{c}$ pairs, one expects the final $(J/\psi)/(N_{c\bar{c}})$ ratio to increase or decrease versus centrality depending on the beam energy [60].

The $J/\psi$ statistical hadronization process has been recently incorporated in a modified approach [51,57]. This approach combines i) directly produced $J/\psi$ followed by nuclear absorption and QGP/HG dissociation and ii) statistically produced $J/\psi$ as in pure statistical models but without the extra charm enhancement factor. This leads to a good agreement with the NA50 $(J/\psi)/(D\gamma)$ data. The agreement is particularly good at the level of the first drop which arises, in this model, from the superposition of direct and statistically produced $J/\psi$. Another interesting aspect from this model is the excitation function of the total $J/\psi$ yield which is expected to be dominated by direct $J/\psi$ at SPS and by statistical $J/\psi$ at RHIC, with a minimum at $\sqrt{s} \sim 50$ GeV. It is important to note that whereas pure statistical models reproduce the measured $\psi'/J_\psi$ ratio, this approach significantly overpredicts it. This leaves room for additional effects [61].

Non-direct charmonium states can be produced not only at the hadronization but also
in the QGP by means of the so-called kinetic recombination process [62]. This mechanism foresees even larger $J/\psi$ yields at RHIC than the statistical hadronization process. Note that all models will face stringent tests with the upcoming data from NA60 at SPS and PHENIX at RHIC.

To conclude on this topic, it is interesting to extrapolate from charmonium production at RHIC to bottomonium production at LHC. Indeed, i) the key parameter for statistical production of charmonium is the number of $c\bar{c}$ pairs and ii) the expected multiplicity of $b\bar{b}$ pairs at LHC is roughly equal to the expected multiplicity of $c\bar{c}$ pairs at RHIC. Therefore, if statistical production of charmonium is confirmed at RHIC, one could expect the same mechanism to occur at LHC for bottomonium states.

6. Charmonium at RHIC

The first charmonium measurements from the PHENIX collaboration are certainly among the most exciting results presented at this conference [63]. The $J/\psi$ signal has been extracted in p-p at $\sqrt{s} = 200$ GeV both in the dielectron channel and in the dimuon channel. Although the present statistics is very limited ($\sim 24(36)$ counts in the dielectron(dimuon) channel), the signal is clearly seen. Thanks to the capability of the PHENIX detector to measure simultaneously the two channels, the first rapidity distribution of $J/\psi$ in p-p at $\sqrt{s} = 200$ GeV has been established. The $J/\psi$ signal has also been extracted in Au-Au reactions in the dielectron channel. The statistics, even more limited than in p-p, does not allow to draw at present solid conclusions on a possible $J/\psi$ suppression or enhancement. However, large suppression factors as well as large enhancement factors seem to be not likely. This will be improved soon since only half of the collected data from the 200 GeV run has been analysed so far. In the next two years the statistics will be enhanced by a factor $\sim 75$ for Au-Au and $\sim 100$ for p-p. Also of great interest will be the coming charmonium measurements in d-A.

7. Next steps

Apart from the forthcoming measurements at RHIC and the analysis of remaining SPS data, new generation experiments are presently being completed or designed.

The HADES experiment [64] at GSI will soon shed light on the DLS low mass dielectron puzzle [65]. The NA60 experiment [66] at SPS will continue in line with the investigations made by NA50 and, in particular, measure the open charm cross-section and the $\psi'$. The ALICE experiment [67] will bring essential information regarding charm and leptons at LHC. Looking even forward into the future, the CBM experiment [68], at the GSI future facility, will allow a new beam energy domain to be explored with simultaneous measurements of low mass dielectrons, charmonia and open charm.

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