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Quarkonium production in p-A collisions

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Abstract. Quarkonium production provides a sensitive window for the study of the gluon structure of nucleons and its modification in nuclei. It also provides a very important means of studying the hot-dense conditions created in high-energy collisions of heavy nuclei and a critical probe to look for deconfinement in this hot-dense matter. I will review, from an experimental point of view, the physics issues as seen in current experimental results for quarkonium production and try to point out the remaining puzzles and how future measurements, along with more theoretical work, can resolve those puzzles. I will discuss production issues including the predicted, but un-observed, J/ψ polarization. Then I will show results from fixed target experiments and discuss cold nuclear matter effects including gluon shadowing, parton energy loss and transverse momentum broadening, and final-state absorption of bound states of heavy quarks ($c\bar{c}$, $b\bar{b}$). In addition, I will highlight the importance of understanding all these effects in cold nuclear matter as a baseline for the search for deconfinement.

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1 Quarkonium production: pp

J/ψ, ψ' and Υ mesons are produced primarily from gluons in the projectile and target. Production of open charm or beauty shares this sensitivity to the gluons as well as to other initial state effects in nuclei such as initial-state gluon energy loss and multiple scattering causing p_T broadening. A longstanding problem in J/ψ production is that models that produce color-singlet states predict cross sections that are several orders of magnitude smaller than those observed by CDF [1]. Although color-octet production (COM) is able to reproduce these cross sections, the matrix elements determined are not universal and do not work for photo-production of J/ψ mesons. A serious problem is that the COM predicts transverse polarization at high p_T, but all measurements (CDF, E866/NuSea [2]) so far see no substantial polarization. One exception to this, shown in Fig. 1, is in the Υ sector, where the Υ_{1S}, like the J/ψ, has no polarization but the Υ_{2S+3S} has maximal transverse polarization [3]. It is possible that this is because the higher Υ states have little feed-down from higher mass states, while both the J/ψ and Υ_{1S} have substantial feed-down ($\sim$30 % for the J/ψ [4]) which would tend to destroy the alignment or polarization. The precise amount of feed-down in the case of the J/ψ is still uncertain, since the most recent results from HERA-B give a somewhat smaller feeddown for the χ_c, 0.21 ± 0.05 [5], than previously seen. Clearly a measurement of the ψ' polarization would be of interest since it does not suffer from feed-down. Also additional measurements of the feeddown fractions are important to help quantify their effect on the nuclear suppression seen for the J/ψ and Υ.

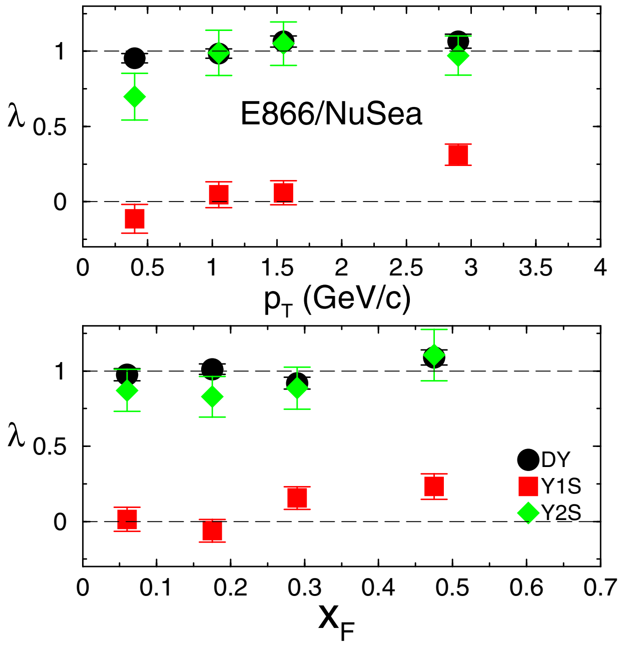

Fig. 1. Polarization versus p_T and x_F for Drell-Yan and Υ production [3]. No polarization ($\lambda = 0$) is observed for the Υ_{1S} while maximal transverse polarization ($\lambda = 1$) is seen for the Υ_{2S+3S}

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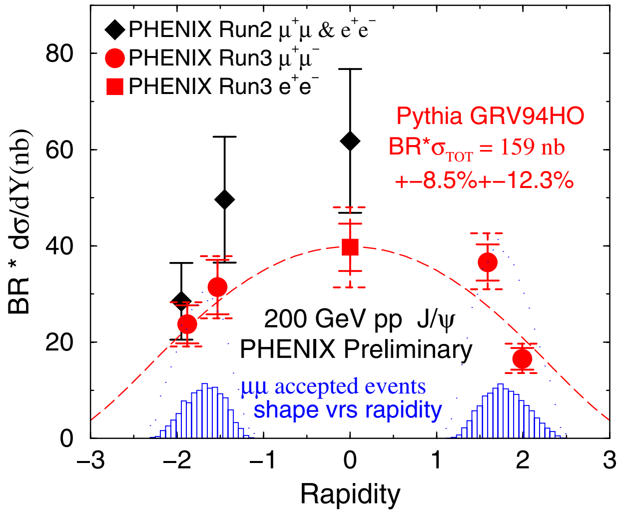

Fig. 2. First measurements (preliminary) of the J/ψ differential cross section for $\sqrt{s} = 200$ GeV pp collisions, versus rapidity, from PHENIX [6]. The dashed curve is a fit to the points using the shape from a Pythia calculation with GRV94HO structure functions that, along with similar fits for other structure functions (not shown), was used to determine the total cross section (indicated on the figure)

The first measurements of J/ψ production at $\sqrt{s} = 200$ GeV from RHIC, shown in Fig. 2, are now becoming available, with much larger statistics expected soon as the luminosity at RHIC increases. With present luminosities, the ψ' is still out of reach, but upcoming higher luminosity runs at RHIC should soon allow both ψ' measurements and polarization measurements for at least the J/ψ. At Fermilab, CDF now has J/ψ measurements down to $p_T = 0$ [7] and can decompose these into direct and those that come from decays of B mesons. As expected, those from beauty decay become increasingly significant at larger p_T, up to 50 %. This feed-down production of J/ψ mesons at RHIC (and LHC) is important, since in a scenario where all primary J/ψ mesons are destroyed by color-screening in a quark-gluon plasma (QGP), there would still be substantial production due to these decays, especially at large p_T, and the effect of the QGP might be masked. A beauty production cross section measurement at RHIC will be necessary to quantify this contribution.

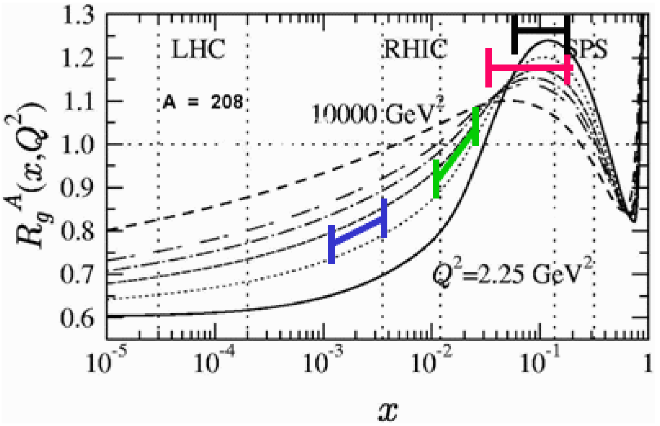

Fig. 3. Nuclear effects on the gluon distribution function according to the EKS98 model [8] showing a reduced number of gluons in the Gold nucleus at small x and an enhancement (anti-shadowing) at moderate x. The colored bars on the plot show the approximate location in x of the PHENIX muon arm (above 10^{-3}), PHENIX central arm (above 10^{-2}), and two lower energy fixed-target experiments, NA50 and E866/NuSea (near 10^{-1})

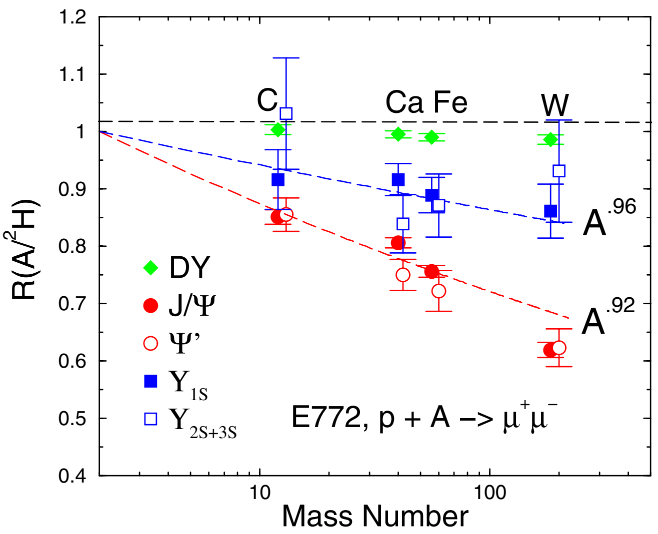

Fig. 4. Nuclear dependence of Drell-Yan, J/ψ, ψ' and Υ total cross sections from E772 [10]. The per nucleon ratio between heavy nuclei and deuterium is shown versus the mass number

2 Nuclear effects: p-A and d-A

Effects of the nuclear medium on the production of heavy quarks include shadowing (depletion at small x) of the gluon distributions in a nucleus, energy loss and multiple scattering of the gluons before the hard interaction, and, for quarkonia, final-state absorption. Shadowing is thought to involve coherence effects that effectively *shadow* the partons inside a nucleus. It can also be thought of as a saturation effect in a nucleus, where at small enough x the gluons from different nucleons overlap and interact with each other causing a promotion through $gg \to g$ interactions to higher x and a corresponding reduction in the population at small x, e.g. as in a recent model called the color-glass condensate (CGC) [9]. Figure 3 shows the EKS gluon shadowing obtained from global fits to deep-inelastic scattering and Drell-Yan measurements along with approximate coverages for J/ψ production in PHENIX and fixed-target experiments.

Figure 4 shows the nuclear suppression of the integrated cross sections from E772 for Drell-Yan, J/ψ, ψ' and Υ, with the J/ψ and ψ' having the strongest suppression. The E866 nuclear dependence versus x_F is shown in Fig. 5, where the suppression is represented using α, from

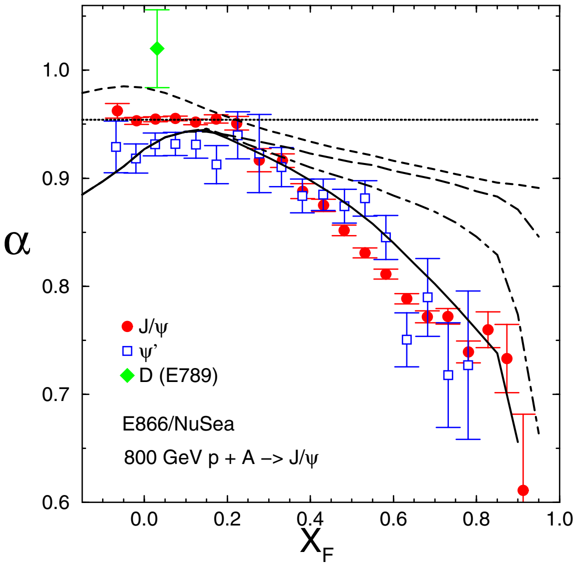

Fig. 5. Data for J/ψ suppression versus x_{F} from E866 [11] (see text). Calculation from Vogt [12] of the nuclear dependence of J/ψ production versus x_{F} showing the relative contributions as they are added: absorption (dotted), gluon shadowing (dashed), initial-state (long-dashed) and final-state (dot-dashed) energy loss and intrinsic charm (solid)

$\sigma_{pA} = \sigma_{pp} \times A^{\alpha}$. $\alpha = 1$ would correspond to no suppression in the per nucleon cross section. Near $x_{\mathrm{F}} = 0$ the suppression of the $c\bar{c}$ states and the lack of suppression of open-charm is thought to be due to absorption of the resonances. At these small x_{F} values the $c\bar{c}$ states move slowly out of the nucleus after their creation and should start to hadronize in the nucleus. Thus, the larger suppression of the ψ' relative to the J/ψ would be due to the larger size and looser binding of the ψ' compared to the J/ψ. At larger x_{F} they traverse the nucleus as pre-resonant $c\bar{c}$ states, only hadronizing far outside the nucleus, and therefore both final resonances experience the same effect. The strong increase of the suppression as x_{F} increases is thought to be due to a combination of shadowing (large x_{F} is small x in the nuclear target) and of energy loss of the gluon in the initial state [12,13]. Some models also argue that *intrinsic charm* components of the initial proton wave function may become increasingly important at larger x_{F} values and would cause an $A^{2/3}$ behavior [14].

As shown in Fig. 6, new data from PHENIX at $\sqrt{s} = 200$ GeV also shows similar features, but so far with much less statistical precision. However, if one looks at the suppression seen at three different energies, $\sqrt{s} = 19$ GeV (NA3 [15]), 39 GeV (E866 [11]) and 200 GeV (PHENIX [6]), the suppression does not scale with x_2 (Fig. 7) but does with x_{F} (Fig. 8). This appears to indicate that shadowing, which should scale with x_2, is not the dominant physics mechanism behind the large x_{F} behavior of the J/ψ. The reason for the apparent scaling with x_{F} remains a puzzle.

As shown in Fig. 9 the PHENIX data and lower energy J/ψ measurements all exhibit the usual p_{T}-broadening, of-

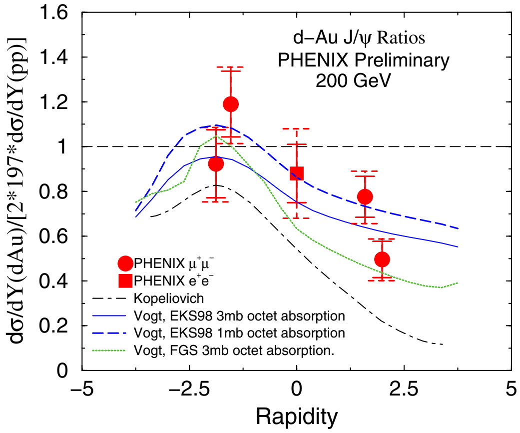

Fig. 6. Nuclear dependence of J/ψ production versus rapidity at $\sqrt{s} = 200$ GeV, from PHENIX [6], compared to several model calculations

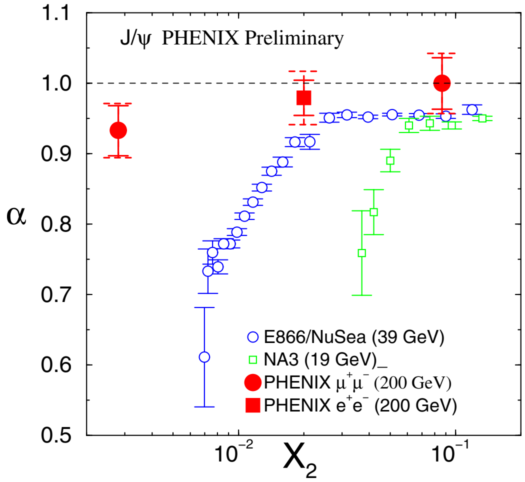

Fig. 7. Nuclear dependence of J/ψ production versus x_2 at $\sqrt{s} = 200$ GeV, from PHENIX, compared to lower energy measurements

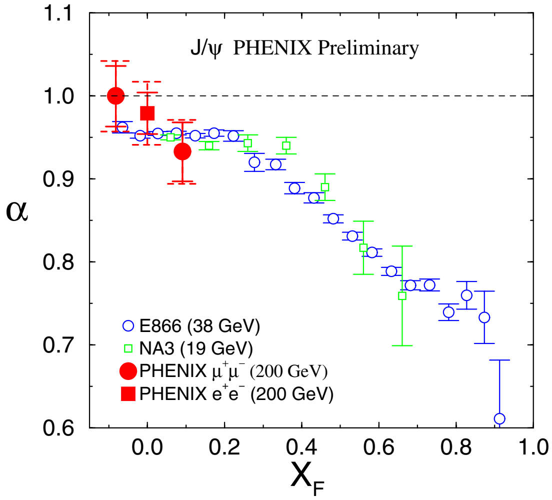

Fig. 8. Nuclear dependence of J/ψ production versus x_{F} at $\sqrt{s} = 200$ GeV, from PHENIX, compared to lower energy measurements

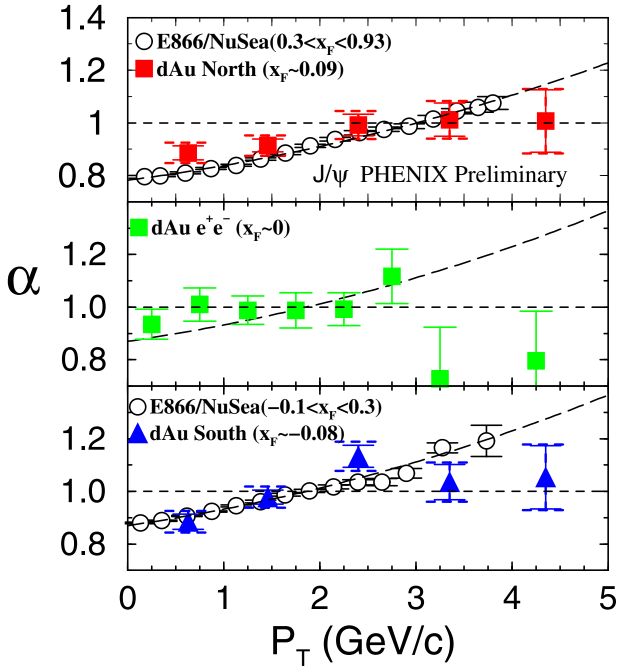

Fig. 9. Nuclear dependence of J/ψ production from PHENIX and E866/NuSea versus p_{T}. Three different x_{F} ranges are shown as indicated on the figure. The black open points are from E866/NuSea ($\sqrt{s}$ = 39 GeV) while the colored closed points are from PHENIX ($\sqrt{s}$ = 200 GeV)

ten called the Cronin effect. This broadening is generally seen in all types of production and is usually attributed to initial-state multiple scattering of the parton from the projectile in the nucleus before the hard production process. The amount of broadening is very similar for the two measurements, at $\sqrt{s} = 39$ and 200 GeV, shown here.

3 Summary and comments

The quarkonium production mechanisms still do not seem to be understood. This leads to uncertainties in the understanding of nuclear effects, e.g. for the absorption which depends on what kind of state the pre-resonant $c\bar{c}$ is in. There appears to be weak gluon shadowing for J/ψ production in $\sqrt{s} = 200$ GeV per nucleon d-Au collisions at RHIC, but statistics are low and a higher luminosity d-Au run at RHIC will be needed in the future to quantify this. The scaling of the suppression with x_{F} and not with x_2 remains a puzzle which I hope more comprehensive theoretical studies including the new RHIC data can begin to resolve. Complementary studies of open charm and of other quarkonia, both experimental and theoretical, are also critical. On the experimental side this, hopefully, will include additions to the RHIC detectors of capable silicon vertex detectors that will be able to clearly identify open charm and beauty. I also believe that NA60, if able to run in the near future, could make significant contributions towards solving the many puzzles in this area, e.g. by providing measurements of ψ' and χ_c and another high statistics J/ψ suppression measurement at a lower $\sqrt{s}$ to help solve the x_{F}-scaling puzzle.

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