Charmonium nuclear interaction at FAIR

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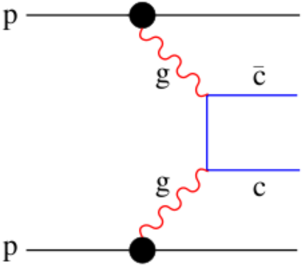
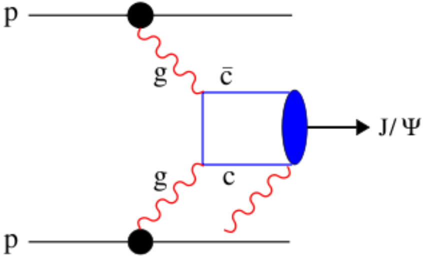
J/ψ and its suppression

- J/ψ suppression in relativistic nuclear collisions is a classical signature of deconfinement transition.
- Inside plasma Debye screening weakens the binding between $c - \bar{c}$ pair: bound state ceases to exist leading to suppression.
- Suppression also seen in $p + A$ collisions due to cold nuclear matter (CNM) effects; needs to be well understood to isolate genuine QGP effects in $A + A$ data
- Suppression observed at SPS ($E_b = 158A$ GeV) has debated theoretical origin; no heavy-ion data below top SPS energy
- CBM experiment at FAIR (SIS-100 and SIS-1300), for the first time, aims at the measurement of J/ψ suppression in low energy ($E_b = 10 - 35A$ GeV) nuclear collisions.
- At SIS-100, opportunity for detailed investigation of charmonium production in $p + A$ collisions





- Stage 1: Hard production of $c\bar{c}$ pair. Generally described by pQCD.
- Stage 2: Formation of the physical resonance from initially compact $c\bar{c}$ pair. Non-perturbative in nature.
- Total number of $c\bar{c}$ pairs are conserved and distributed into open charm and different charmonium states: J/ψ, ψ', χ_C

J/ψ production in elementary collisions contd...

- Stage I.Formation of $c\bar{c}$ pair
  - At leading order (LO) $q\bar{q}$ annihilation and gg fusion are important.
  - At higer collision energies (eg: RHIC, LHC), gluons are only important
  - At lower energies (eg; SPS, FAIR) quark annihilation dominates over gluonic fusion at higher x_F. Critical value depend on the energy of collision.
- Stage II: Formation of resonance
  - Initially produced $c\bar{c}$ has to neutralize its color before forming a physical resonance.
  - Different models of color neutralization:CEM, CSM, COM
  - Experimentally in pp collisions, 95% open charm, 1.2%J/ψ, 3%χ_C and 0.3% ψ'.

Time evolution of J/ψ formation

- Different time scales involved with J/ψ production.
- $c\bar{c}$ formation time: $\tau_{c\bar{c}} \simeq \frac{1}{2m_C}$
- color neutralization time: $\tau_0 = \frac{1}{\sqrt{2m_C \Lambda_{QCD}}} \simeq 0.25$ fm
  (D. Kharzeev and H.Satz, Z. Phys. C 60 (1993) 389)
- $\tau_{c\bar{c}}$ and τ_0 would be same for all resonnaces.
- Resonance formation time (τ_R) would be longer for excited states, from potential model studies: $\tau_R(J/\psi) \simeq 0.35$ fm, $\tau_R(\chi_C, \psi') \simeq 1$ fm.
  (F. Karsch and H.Satz, Z. Phys. C 51 (1991) 209)
- All the times are estimated in the $c\bar{c}$ rest frame; in the laboratory longer formation time.

Time evolution of J/ψ formation contd...

- Amount of dilation would depend on the collision energy.
- Formation length in the laboratory frame:

$$d_0 = \gamma\beta\tau_0 = \frac{P_A}{M}\tau_0,$$

P_A: lab momentum and M: mass of the $c\bar{c}$ state.

- If P denotes the CMS momentum of the state then

$$P = \gamma_{CMS} P_A - \gamma_{CMS}\beta_{CMS}\sqrt{P_A^2 + M^2},$$

β_{CMS}: transformation from laboratory frame to CMS frame.

- The Feynmann scaling variable of the $c\bar{c}$ state: $x_F = \frac{P}{P_{max}}$

Time evolution of J/ψ formation contd...

- The maximum CMS momentum the $c\bar{c}$ can have in an elementary reaction

$$n + n \rightarrow J/\psi + X$$

would be for the configuration

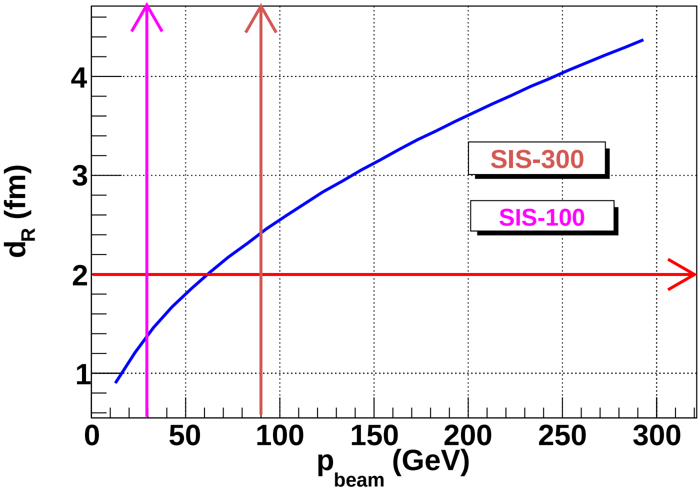
$$s = (\sqrt{Pmax^2 + M^2} + \sqrt{P_{max}^2 + 4m^2})^2$$

M: mass of $c\bar{c}$ and m nucleon mass.

- The maximum momentum reads as

$$P_{max} = \sqrt{\left(\frac{s + 4m^2 - M^2}{2\sqrt{s}}\right)^2 - 4m^2},$$

Beam energy dependence of the formation length



- Calculation at mid-rapidity ($x_F = 0$)

J/ψ production in $p + A$ collisions

- In $p + A$ collisions, charmonia are produced in the nuclear medium.
- Momentum dependence would decide their state during passage through the target.
- Very fast in the nuclear rest frame: nucleus sees the passage of color octet $c\bar{c}$ state, same for all charmonium states
- Very slow in nuclear rest frame: nucleus sees the fully developed resonance, different for different charmonium states
- Average range of nuclear interaction $r_{NN} \simeq 2$ fm.
- Depending on collision energy and x_F different situation can arise:
  1. $d_R < 2$ fm, full resonance formation occurs with in the range of the target nucleon on which it is produced. Nucleus sees the physical state over entire path
  2. $d_0 < 2fm$ but 2 fm $< d_R < L_A$ nucleus partly see the color singlet pre-resonance state partly the full resonance
  3. 2 fm $< d_0 < L_A$ color octet and color singlet

Cold nuclear matter effects

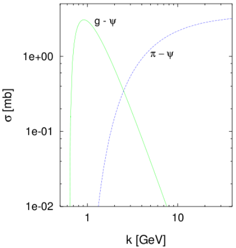
- Initial state modification of the parton densities inside the target nucleus: modifies the overall $c\bar{c}$ production rate.
- Final state dissociation of the nascent $c\bar{c}$ pairs by the spectator nucleons inside the target, in the pre-resonance/resonance stage:

$$S_\psi = e^{-n_0 \sigma_\psi L_A}$$

n_0: nuclear density, L_A: path traversed by the $c\bar{c}$ pair inside target.

- For a given target, suppression is sensitive to the J/ψ-N inelastic cross section.
- Different theoretical prescriptions for J/ψ-N cross section.
- No measurement till date available for validation.

J/ψ dissociation in nuclear medium:I



D. Kharzeev and H. Satz, Phys. Lett. B 334 (1994) 155

- Gluonic dissociation of J/ψ:

$$\sigma_{diss}(g - J/\psi) \simeq (k - \Delta E\psi)^{1.5} k^{-5}$$

- Convolute with hadron pdf to obtain hadronic dissociation cross section:

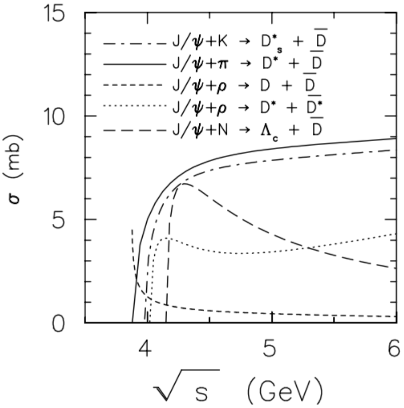
$$\sigma_{diss}(h - J/\psi) \simeq \sigma_{geo}(1 - \lambda)^{6.5}$$

- Hadronic dissociation shows strong threshold damping

J/ψ dissociation in nuclear medium:I (contd...)

- Dissociation cross section attains asymptotic value, $\sigma_{geom} = \pi r^2_{j/\psi} \simeq 2 - 3$ mb, only for large hadron momentum
- Slow hadrons do not contain sufficiently hard gluons
- Slow hadrons can not break up J/ψ
- slow J/ψ in nuclear matter are not dissociated
- CAVEAT: theory becomes exact at $m_Q \rightarrow \infty$

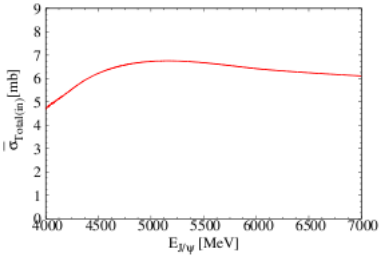
J/ψ dissociation in nuclear medium:II



K. Haglin *et al.*, PRC 2000

- Estimation of J/ψ dissociation in a hot hadronic medium
- J/$\psi - N$ inelastic interaction via: J/$\psi + N \rightarrow \Lambda_C + \bar{D}$
- Sharp rise close to threshold

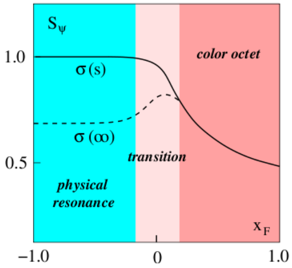
Dissociation from hadronic model:II



R. Molina, C. W. Xiao and E. Oset, PRC 2012

- Most recent estimate of $J/\psi - N$ inelastic interaction.
- Considers several disociation channels including $\Lambda_C \bar{D}$ and $D\bar{D}$.
- Effect of Fermi motion of nucleons taken into account

A test case: $p + Pb$ collisions at 160 GeV



D. Kharzeev and H. Satz, PLB 1995

- $x_F < 0.2$ Resonance region, medium sees fully formed J/ψ
- $x_F > 0.1$ Color octet region, medium sees colored $c\bar{c}$ pair
- Suppression sensitive to the adopted prescription for cross section, in the resonance region
- Two different estimatons for dissociation cross sections:difference is $\simeq 20\%$

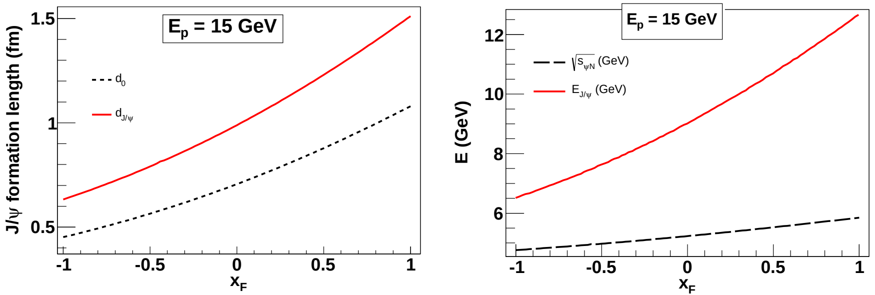
$p + Pb$ collisions at 160 GeV contd...

- No $p + A$ data by NA50 Collaboration at 160 GeV
- J/ψ production in 158 GeV $p + A$ collisions by NA60 Collaboration
- Phase space coverage: $0.28 < y_{cm} < 0.78$::$0.1 < x_F < 0.3$
- color octet region: experimentally well studied at SPS and higher energies
- resonance region: experimentally unexplored: not investigated at all

$p + A$ collisions at FAIR SIS-100

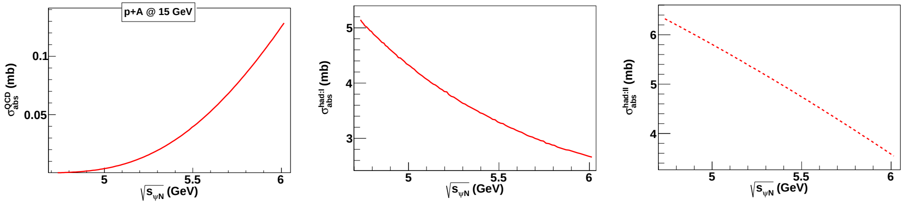
- Precise multidifferential measurement of charmonium production with proton beams up to 30 GeV.
- Possiblity to measure for the first time the behavior of physical J/ψ and excited charmonium states in normal nuclear matter.
- Measurement close to kinematic production threshold:: $E_{th}^{J/\psi} \simeq 12.2$ GeV, $E_{th}^{\psi'} \simeq 15.7$ GeV, $E_{th}^{\chi_c} \simeq 14.6$ GeV

J/ψ production in 15 GeV $p + A$ collisions



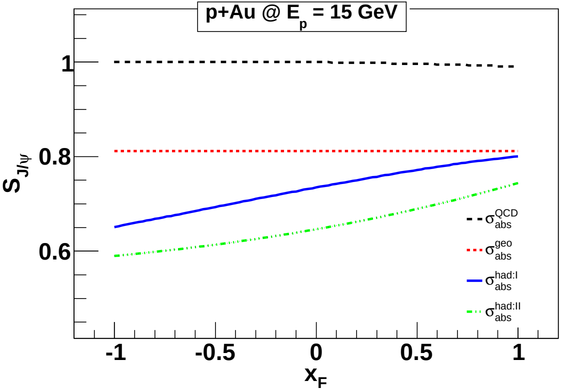
- Over the entire x_F range, $d_R < 2$ fm.
- Physical resonance passes through the nucleus over entire path length
- Energy of the resulting $\psi - N$ interaction remains close to the threshold.

Dissociation cross sections at FAIR SIS-100



- Cross sections calculated as a function of J/ψ-N CMS energy
- Gluo-dissociation shows opposite behavior compared to hadronic models

Calculation of J/ψ survival probability

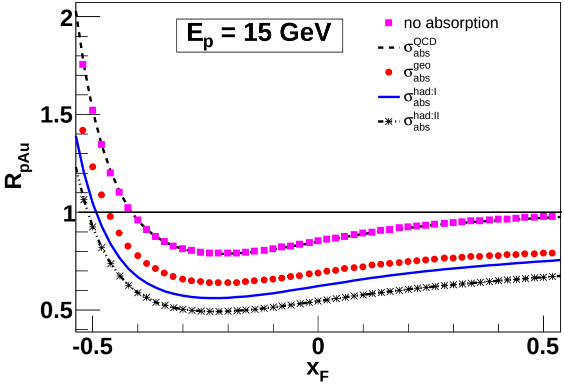


- Distinguishably different suppresion patterns for different mechanisms
- Gluo dissociation produces negligible suppression
- x_F independent suppression for geometric cross section
- Hadronic models predict larger suppression for slower J/ψ ($x_F < 0$)

Experimental observable: Nuclear modification factor (R_{pA})

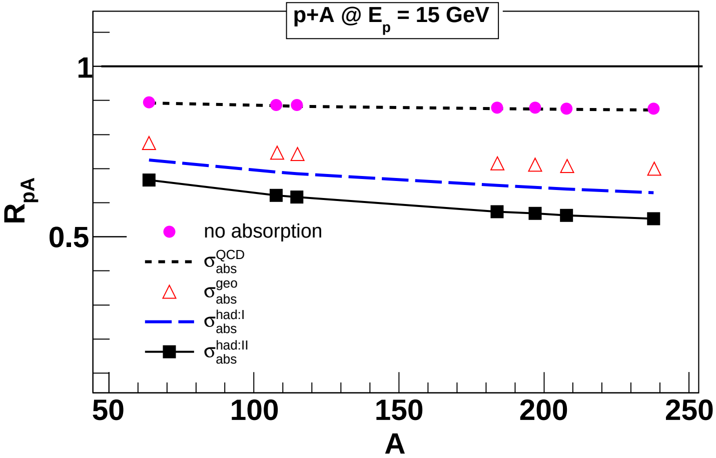
- Experiments would measure overall production cross section, rather than survival probabbilities
- Depend on other CNM effects
- Define nuclear modification factor as ratio of production cross sections in $p + A$ and $p + p$ collisions
- Include initial state shadowing effects governing over all $c\bar{c}$ production rate
- Use EPS09 nPDF set for shadowing parameters

J/ψ suppression in $p + Au$ collisions at FAIR SIS-100



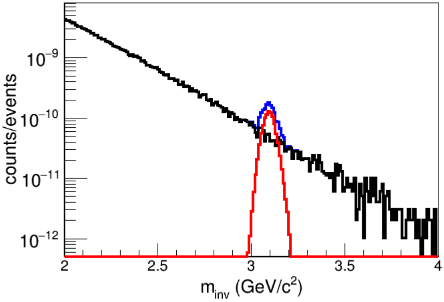
- Negligible production cross section beyond $|x_F| > 0.5$
- Suppression pattern sensitive to the choice of absorption cross section
- Possible to isolate the shadowing effects measuring $J/\psi/D$ ratio.

J/ψ R_{pA} at FAIR SIS-100



- Target mass dependence of inclusive suppression pattern

J/ψ reconstruction @ FAIR SIS-100



- Reconstructed J/ψ spectra in 15 A GeV central $Ni + Ni$ collisions
- Clearly visible peak over the combinatorial background
- Feasible $p + A$ measurements
- Phase space of the reconstructed mesons:$-0.2 < y_{cms} < 0.4$::$-2.3 < x_F < 0.45$

Summary and outlook

- To summarize ...
  - At FAIR slow J/ψ mesons would be produced
  - Provides excellent opportunity to perform very first measurement of behavior of physical J/ψ in normal nuclear matter
  - World data collected so far is not of much use, pioneering measurements at FAIR
  - Such measurements seem to be feasible with the CBM SIS-100 muon set up
  - Crucial for interpretation of data in heavy-ion collisions
- Scope of improvements ...
  - Investigate the excited states (χ_C and ψ')
  - Include the effect of feed down to J/ψ production
  - Investigate the other initial state effect like energy loss
  - Estimation at other relevant energies

Refrences

- " Charmonoum interaction in nuclear matter", D. Kharzeev and H. Satz, Phys. Lett. B 1995
- "HICforFAIR Workshop: Heavy flavor physics with CBM" by H. Satz, FIAS, May 2014
- "CBM Collaboration Meeting: On the charm of p-A collisions" M. Deveaux, Goethe University Frankfurt and CBM, April, 2016
- M. Deveaux, private communication