Charmonium production in $\bar{p}$-induced reactions on nuclei

Alexei Larionov[1,2,a], Marcus Bleicher[1,3], Albrecht Gillitzer[4], and Mark Strikman[5]

[1] *Frankfurt Institute for Advanced Studies (FIAS), D-60438 Frankfurt am Main, Germany*
[2] *National Research Centre "Kurchatov Institute", 123182 Moscow, Russia*
[3] *Institut für Theoretische Physik, J.W. Goethe-Universität, D-60438 Frankfurt am Main, Germany*
[4] *Institut für Kernphysik, Forschungszentrum Jülich, D-52425 Jülich, Germany*
[5] *Pennsylvania State University, University Park, PA 16802, USA*

Abstract. The production of charmonia in the antiproton-nucleus reactions at $p_{\text{lab}} = 3 - 10$ GeV/c is studied within the Glauber model and the generalized eikonal approximation. The main reaction channel is charmonium formation in an antiproton-proton collision. The target mass dependence of the charmonium transparency ratio allows to determine the charmonium-nucleon cross section. The polarization effects in the production of χ_{c2} states are evaluated.

1 Introduction

Investigation of charmonium-nucleon interactions is important for several reasons: (i) Interpretation of J/ψ suppression in relativistic heavy-ion collisions and separation of the charmonium dissociation mechanism in a quark-gluon plasma from cold nuclear matter effects. (ii) Constraining the QCD-inspired models of charmonia. (iii) Growing understanding of nonperturbative vs perturbative QCD aspects, such as factorization theorem, color dipole cross section, color transparency phenomenon.

Charmonium formation $\bar{p}p \rightarrow R$ ($R = J/\psi, \psi', \chi_c, \ldots$) on a nuclear target proton has been proposed long ago [1, 2] to address the genuine charmonium-nucleon cross section, since the charmonium formation length is short in this case. In this talk we present some results of our detailed studies [3, 4] of $J/\psi, \psi'$ and χ_c production in $\bar{p}A$ interactions at threshold.

2 Glauber model calculation of J/ψ and ψ' production

Charmonium production cross section in antiproton-nucleus interaction is calculated as

$$\sigma_{\bar{p}A \rightarrow R(A-1)^*} = v_{\bar{p}}^{-1} \int d^2b \int_{-\infty}^{\infty} dz \, \mathrm{e}^{-\sigma_{\bar{p}N}^{\text{inel}}(p_{\text{lab}}) \int_{-\infty}^{z} dz' \rho(z',b)} \Gamma_{\bar{p} \rightarrow R}(z,b) \, \mathrm{e}^{-\int_{z}^{\infty} dz' \rho(z',b) \sigma_{RN}^{\text{eff}}(p_R, z'-z)} , \qquad (1)$$

where $v_{\bar{p}} = p_{\text{lab}}/E_{\bar{p}}$ is the antiproton velocity. $\Gamma_{\bar{p} \rightarrow R}$ is the antiproton width with respect to the charmonium production:

$$\Gamma_{\bar{p} \rightarrow R}(z,b) = \int \frac{2d^3p}{(2\pi)^3} \, v_{\bar{p}p}(s) \, \sigma_{\bar{p}p \rightarrow R}(s) \, f_p(z,b,\mathbf{p}) , \qquad (2)$$

[a]e-mail: larionov@fias.uni-frankfurt.de

where $f_p(z, b, \mathbf{p})$ is the proton phase space occupation number chosen here for simplicity to be the local Fermi distribution, $f_p(z, b, \mathbf{p}) = \Theta(p_{F,p} - |\mathbf{p}|)$;

$$\sigma_{\bar{p}p \to R}(s) = \frac{(2J_R + 1)\pi}{s/4 - m_N^2} \frac{s\Gamma_{R \to \bar{p}p}\Gamma_R}{(s - m_R^2)^2 + s\Gamma_R^2} \tag{3}$$

is the charmonium formation cross section; $v_{\bar{p}p} = \sqrt{s(s/4 - m_N^2)}/E_{\bar{p}}E_p$ is the $\bar{p}p$ relative velocity. We assume the proton energy $E_p = m_N - B$, where $B \simeq 8$ MeV is the nucleus binding energy per nucleon.

The exponential factors in Eq.(1) account for the antiproton and charmonium survival probabilities. The effective charmonium-nucleon cross section is chosen as $\sigma_{RN}^{eff}(p_R, z) = \sigma_{RN}(p_R)\kappa(z)$, where $\sigma_{RN}(p_R)$ is the total interaction cross section of the entirely formed charmonium with a nucleon; $\kappa(z)$ is the charmonium position dependent function, $\kappa(z) < 1$ for $z < l_R$ and $\kappa(z) = 1$ for $z \geq l_R$, which takes into account the charmonium formation length l_R according to the color diffusion model [2]. The cross sections σ_{RN} have been studied by several groups of authors (c.f. [5–8]) and are expected to be within 3.5-7 mb for J/ψ, 0-20 mb for ψ', and 7-16 mb for χ_c-states.

Fig. 1 shows the J/ψ and ψ' production cross sections on the lead target as a function of the $\bar{p}$-beam momentum. We have chosen three representative values of the $J/\psi N$ cross section: $\sigma_{J/\psi N} = 0$, 3.5 and 6 mb. For the $\psi' N$ cross section, we considered only the two limiting cases, i.e. $\sigma_{\psi' N} = 0$ and 20 mb [7]. The formation length for J/ψ can be evaluated as $l_{J/\psi} = 2p_{J/\psi}/(m_{\psi'}^2 - m_{J/\psi}^2) \simeq 0.1$fm $p_{J/\psi}$/GeV. Thus, at $p_{J/\psi} \simeq p_{lab} \simeq 4$ GeV/c the J/ψ formation length is 0.4 fm which is even smaller than the internucleon spacing, $d_{NN} \simeq 2$ fm. As a consequence, the J/ψ production cross sections shown in Fig. 1 are almost insensitive to the formation length effects. For ψ', the formation length is larger ($l_{\psi'} \simeq 2l_{J/\psi}$, c.f. [7]), although even in this case formation length practically does not influence the production cross sections. On the other hand, we observe the sensitivity of the charmonium production cross section to the chosen charmonium-nucleon cross section.
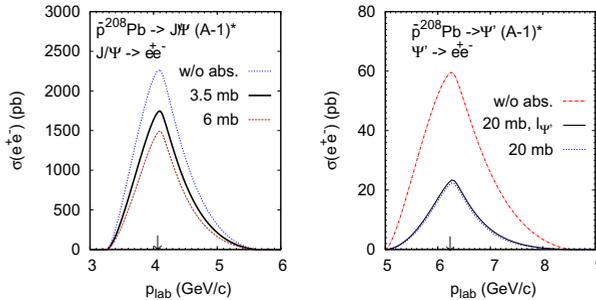

Figure 1. J/ψ and ψ' production cross sections on Pb. Arrows show the beam momenta for the on-shell charmonium production on the proton target: 4.07 GeV/c for J/ψ and 6.23 GeV/c for ψ'.

Fig. 2 displays the transparency ratio of the J/ψ production

$$\frac{\sigma_{\bar{p}A \to J/\psi(A-1)^*}}{\sigma_{\bar{p}^{27}\text{Al} \to J/\psi^{26}\text{Mg}^*}} \left(\frac{27}{A}\right)^{2/3} \tag{4}$$

at the on-shell peak beam momentum $p_{lab} = 4.07$ GeV/c as a function of the target mass number. The scaling factor $\propto A^{-2/3}$ accounts for the surface absorption of the antiproton. In general, the

transparency ratio is expected to be a more robust observable sensitive to charmonium-nucleon cross section, since the possible uncertainties in the production width $\Gamma_{\bar{p}\rightarrow R}$ cancel out in Eq.(4). Indeed, we see that the transparency ratio is quite sensitive to the $J/\psi N$ cross section, although for the quantitative conclusions one should carefully take into account the empirical details of the nuclear density profiles at the surface region.
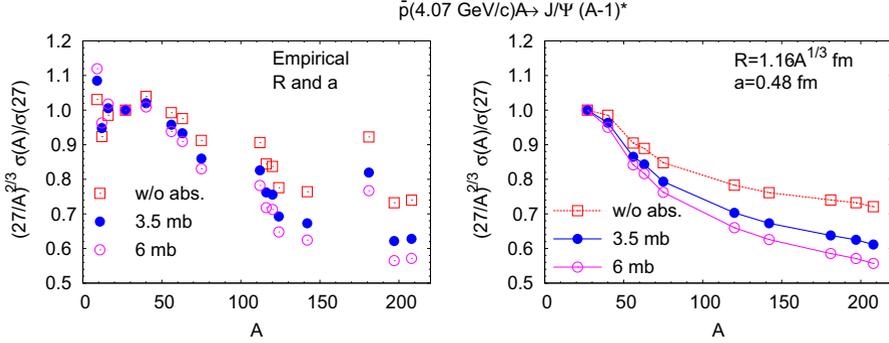

Figure 2. Left panel – transparency ratio, Eq.(4), for nuclei ^{9}Be, ^{12}C, ^{16}O, ^{27}Al, ^{40}Ca, ^{56}Fe, ^{63}Cu, ^{75}As, ^{112,116,120,124}Sn, ^{142}Ce, ^{181}Ta, ^{197}Au and ^{208}Pb calculated with empirical parameters of the proton and neutron density profiles. Right panel – same for heavy nuclei excluding ^{112,116,124}Sn applying the two-parameter Fermi distribution with radius R and diffuseness a as indicated.

3 $\chi_{cJ}(J = 0, 1, 2)$ production

Since the mass splitting between the different χ_{cJ} states is small ($\sim$ 140 MeV), the nondiagonal transitions $\chi_{cJ_1}N \rightarrow \chi_{cJ}N$ should be easily possible. The amplitudes of such transitions can be calculated from the Clebsch-Gordan decomposition of a physical $\chi_{cJ}(\nu)$ state with helicity ν in the basis of the $c\bar{c}$ states with fixed orbital (L_z) and spin (S_z) magnetic quantum numbers [4]: $M_{J\nu;J_1\nu}(0) = \sum_{L_z,S_z}\langle J\nu|1L_z; 1S_z\rangle M_{L_z}(0)\langle 1L_z; 1S_z|J_1\nu\rangle$. With a help of the optical theorem, the forward scattering amplitude $M_{L_z}(0)$ can be expressed via the total interaction cross section σ_{L_z} of a $c\bar{c}$ pair with fixed L_z with a nucleon: $M_{L_z}(0) = 2ip_{\text{lab}}m_N\sigma_{L_z}(1 - i\rho_{\chi N})$, with $\rho_{\chi N} = \text{Re}M_{L_z}(0)/\text{Im}M_{L_z}(0) = 0.15 - 0.30$. In Ref. [7], the cross sections σ_{L_z} have been calculated by using the nonrelativistic quarkonium model and the QCD factorization theorem. Their values, $\sigma_{\pm 1} = 15.9$ mb and $\sigma_0 = 6.8$ mb, differ by a factor of two, which is the ratio of the transverse size squared for the $c\bar{c}$ states with $L_z = \pm 1$ and $L_z = 0$. This directly leads to the finite nondiagonal transition amplitudes: $M_{20;00}(0) = 2ip_{\text{lab}}m_N\frac{\sqrt{2}}{3}(\sigma_1 - \sigma_0)(1 - i\rho_{\chi N})$, $M_{2\pm 1;1\pm 1}(0) = \pm 2ip_{\text{lab}}m_N\frac{1}{2}(\sigma_1 - \sigma_0)(1 - i\rho_{\chi N})$.

By applying the generalized eikonal approximation (GEA)(c.f. [9] and refs. therein), we have calculated the helicity ratio

$$\mathcal{R} = \frac{\chi_{c2}(0)}{[\chi_{c2}(0) + \chi_{c2}(\pm 1)]|B_0|^2} \tag{5}$$

for χ_{c2} production in $\bar{p}^{208}$Pb collisions. Here, B_0 is the helicity amplitude $\bar{p}p \rightarrow \chi_{c2}(\nu = 0)$, $|B_0|^2 = 0.13 \pm 0.08$ [10]. Fig. 3 shows the ratio (5) at small transverse momentum as a function of $\bar{p}$-beam momentum. In the absence of any $\chi_{cJ}N$ interactions, one has $\mathcal{R} = 1$. However, the interference term of the direct $\bar{p}p \rightarrow \chi_{c2}(0)$ and the two-step $\bar{p}p \rightarrow \chi_{c0}(0)$, $\chi_{c0}(0)N \rightarrow \chi_{c2}(0)N$ amplitudes leads to

~ 30% deviations of the helicity ratio from one due to the strong coupling of the χ_{c0} state with $\bar{p}p$ channel.
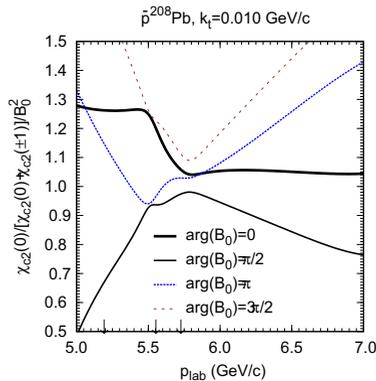

Figure 3. Helicity ratio (5) for the different values of the phase difference of the $\nu = 0$ helicity amplitudes for χ_{c2} and χ_{c0}. Arrows show the beam momenta for the on-shell charmonium production on the proton target: 5.194, 5.553 and 5.727 GeV/c for χ_{c0}, χ_{c1} and χ_{c2}, respectively.

4 Summary

We have performed the Glauber and the GEA calculations of charmonium production in $\bar{p}A$ collisions close to threshold. To summarize the main results: The strong sensitivity of J/ψ (ψ') production to the genuine $J/\psi N$ ($\psi'N$) cross sections is confirmed. For the quantitative determination of the $J/\psi N$ ($\psi'N$) cross sections, the density profiles of the target nuclei are important. Polarization effects in the χ_{c2} production in the *unpolarized* $\bar{p}$ collisions with nuclei appear as a consequence of the different transverse sizes of $c\bar{c}$ pair with $L_z = \pm 1$ and $L_z = 0$. These findings could be useful for the planning of the forthcoming PANDA experiment at FAIR.

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