

**INTERMEDIATE ENERGY ANTIPROTON-NUCLEUS REACTIONS TO TEST
QUANTUM CHROMODYNAMICS**

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1. - Introduction

Antiproton annihilation in nuclear matter at intermediate energy plays a special role in testing fundamental aspects of Quantum Chromodynamics.

Quantitative tests of QCD are usually performed by studying high momentum transfer reactions, where asymptotic freedom and factorization theorems allow detailed predictions based on short-distance quark-gluon subprocesses. Along this line, the perturbative QCD (PQCD) analysis of exclusive amplitudes¹ makes specific predictions, which are generally consistent with experiments at transverse momenta beyond some GeV/c. For example, large momentum transfer exclusive reactions ($A+B \rightarrow A+B$) are experimentally observed to obey the scaling behaviour $s^{2(n_A + n_B - 1)}$, where n_i ($i = A, B$) is the number of point-like constituents of the particles A and B, as predicted by PQCD². Similarly, two-body elastic hadron-hadron scattering³ and exclusive two-photon reactions⁴ are good evidences of the relevance of PQCD to exclusive hadron scattering.

Other predictions, like violation of hadron-helicity conservation⁵, angular and energy behaviour of the spin-spin correlation asymmetry

$$A_{NN} = \frac{d\sigma(\uparrow\uparrow) - d\sigma(\uparrow\downarrow)}{d\sigma(\uparrow\uparrow) + d\sigma(\uparrow\downarrow)} \quad (1)$$

measured in large momentum transfer pp elastic scattering⁶, and a novel phenomenon, based on the concept of a nucleus as a "color filter", and called "color transparency"⁷, show, on the contrary, that leading-twist PQCD is not the whole story⁸.

We know, indeed, that perturbative calculations in QCD must break down at momentum transfers of the order of $\Lambda_{\overline{MS}}$, the invariant momentum scale where the QCD running constant $\alpha_s(Q)$ becomes large. A recent determination at LEP⁹ gives the value for $\Lambda_{\overline{MS}} = 216 \pm 85$ MeV. At the same time, scaling laws characteristic of the underlying quark and gluon degrees of freedom, in particular the Bjorken scale invariance of electroproduction structure functions, and the inverse power law fall-off of electromagnetic form factors, are clearly evident at momentum transfers of a few GeV/c or less. Thus, the most challenging testing ground of the theory can be identified at the intersection between perturbative and non-perturbative physics, where coherent effects and hadron substructures become manifest, which requires the detailed study of hadronic and nucleon phenomena at moderate energies and momentum transfers.

A nuclear target is a very useful tool for sorting out competing QCD subprocesses and elucidating fundamental aspects of QCD¹⁰. We recall here three specific predictions of QCD in nuclei: the already mentioned color transparency effect; the hadronization process, which is not less relevant than the opposite case of asymptotic freedom; the existence of bound states due to pure gluonic forces¹¹. In a sense, as properly underlined by S. Brodsky¹², "the background from nuclear field plays the role in QCD that external magnetic and electric fields provide in atomic physics, allowing one to modify and to probe the basic parameters of fundamental interactions".

Finally, in testing QCD at intermediate energy with a nuclear target, antiprotons play a unique role^{12,13}. In fact, in a total annihilation process, like inclusive lepton- and photon-pairs production, or exclusive two-body final states, all the valence quarks and valence antiquarks of the initial system are found to annihilate at distances of the order of the proton scale, $\sim 1/M_p$. In closed and open charm production near threshold, $\bar{p}p \rightarrow J/\Psi$ $\bar{p}p \rightarrow \Lambda_c \bar{D}$, the transverse momentum is controlled by the charm scale, $\sim 1/m_c$. Thus, automatically, the annihilation process involves short distances and therefore is in the perturbative domain.

In this paper I shall limit my discussion to the color transparency case, which exhibits many special reasons of interest. First, PQCD gives straightforward predictions for color transparency, which are in clear contrast to more conventional pictures, like the Glauber picture. Second, the only existing test of color transparency¹⁴ shows a momentum dependence which is in apparent disagreement with PQCD above some critical momentum. Third, color transparency is one of the ways to shed light on the confinement mechanism, i.e. to know how quarks or gluons produced in hard processes at small distances go over into observable hadrons, or, in other words, which is the mechanism of quark and gluon hadronization.

It should be recalled, in fact, in discussing the tests of QCD, that all the positive confirmations of the theory based on the study of hard processes - for example, hadronic jet production, deep-inelastic

lepton-nucleon scattering, etc. - are characterized by one general feature: they are independent of the hadronization mechanism¹⁵.

I shall show that a direct natural way to study color transparency and the process of hadronization in QCD is to measure quasi-elastic J/Ψ production by antiprotons on a nuclear target. J/Ψ production by antiprotons has also another advantage: unlike J/Ψ photoproduction, this process can provide direct information on the J/Ψ - nucleon cross section. Needless to say, this quantity is crucial in checking the effective J/Ψ absorption in nuclear matter, which is the most reliable experimental signature up to now of quark-gluon plasma phase transition. The feasibility of such a formation experiment will be demonstrated by evaluating the charmonium production cross section in nuclei and using machine parameters taken from the SuperLEAR Project.

2. - Color transparency

The color transparency effect is based on the concept of the nucleus as a "color filter" in QCD. Briefly, the idea goes back to the so-called "diffractive dissociation", as explained in the second half of the fifties in the classical papers by Feinberg and Pomeranchuk¹⁶ and Good and Walker¹⁷: a characteristic quantum effect which is relevant in the build-up of the total hadron-hadron cross section at high energy. In a typical dissociation event the diffraction arises from the variability of the absorption amplitude as a function of the internal coordinates of the projectile wave function. In QCD, a rapidly moving hadron is a complicated system of partons (quarks and gluons) characterized by a color singlet Fock-state vector wave function:

$$|N\rangle = \left| \begin{array}{c} 3q \\ 3q+kg \\ 3q+kg+mqq \end{array} \right\rangle \quad (1)$$

The components of the projectile Fock-state vector with small transverse size have a small color dipole moment and thus will interact weakly with the nucleons¹⁸. Conversely, the Fock components of normal hadronic size will interact strongly and will be nearly totally absorbed during their passage through the nucleus¹⁹. In short, a nuclear target will act as a "filter", removing from the beam all but short-range components of the projectile wave function²⁰.

Large momentum transverse quasi-exclusive reactions are controlled, in perturbative QCD, by small color-singlet valence-quark Fock components of transverse size $b_{\perp} \sim 1/Q$. This implies that the cross section for soft initial- and final-state interactions with other nucleons in the nucleus will vanish as the energy scale increases and thus these hard reactions occur without initial- and final-state corrections. The result is that at large momentum transfers and energies quasi-exclusive reactions occur *additively* in the nuclear volume. This phenomenon is called QCD "*color transparency*".

In other words, according to QCD, the cross sections of hadronic interactions depend on the size of the hadrons. Hadrons are "white" objects and their interaction is due to color charge distributed in a region R_h . Since hard processes are governed by small size transverse component of hadrons $r_{\perp} \sim$

$1/Q$, at high energy it is possible to expect a small absorption in these processes: the nucleus should be "color transparent" to the projectile.

Thus QCD predicts - for example - that the transparency ratio T of the quasi-elastic J/Ψ production by antiprotons

$$\bar{p}p \rightarrow J/\Psi \quad (2)$$

will be additive in the proton number of a nuclear target

$$T = \frac{d\sigma/dQ^2(\bar{p}A \rightarrow (A-1) J/\Psi)}{d\sigma/dQ^2(\bar{p}p \rightarrow J/\Psi)} \rightarrow Z^1 \quad (3)$$

for $Q^2 \rightarrow \infty$.

This is in sharp contrast with the conventional Glauber picture of nuclear absorption, in which the quasi-elastic scattering occurs primarily on the front surface of the nucleus and thus the above ratio should be proportional to $Z^{2/3}$. Moreover, in the Glauber scheme the transparency would be expected to be energy independent, while, according to PQCD expectations, the transparency would increase as the momentum transfer increases.

Up to now, only one test of QCD color transparency has been performed. It is the measurement of quasi-elastic large-angle pp scattering from several nuclei (Li, C, Al, Cu, Pb) compared to pp elastic scattering, at incident proton momenta of 6, 10 and 12 GeV/c¹⁴. The results, shown in Fig.1, indicate that the transparency T is indeed energy dependent and increases as the incident momentum increases, in agreement with PQCD. However, the 12 GeV/c data show a significant drop in T , which reaches, surprisingly, the value of the normal Glauber absorption (see Fig.1).

At this point, it is interesting to recall that just in this kinematical region one of the most serious challenges to QCD also occurs, namely, the behaviour of the spin-spin correlation asymmetry A_{NN} measured in large momentum transfer pp elastic scattering⁶. In fact, at $p = 11.75$ GeV/c and $\theta_{c.m.} = \pi/2$, A_{NN} rises to 60%, corresponding to four times higher probability for protons to scatter with their incident spins both normal to the scattering plane and parallel to each other. Moreover, data show a striking energy and angular dependence, not expected from the slowly changing PQCD predictions²¹. The onset of this apparently new phenomenon at $\sqrt{s} = 4.9$ GeV appears to signal either new degrees of freedom or exotic components in the dibaryon system.

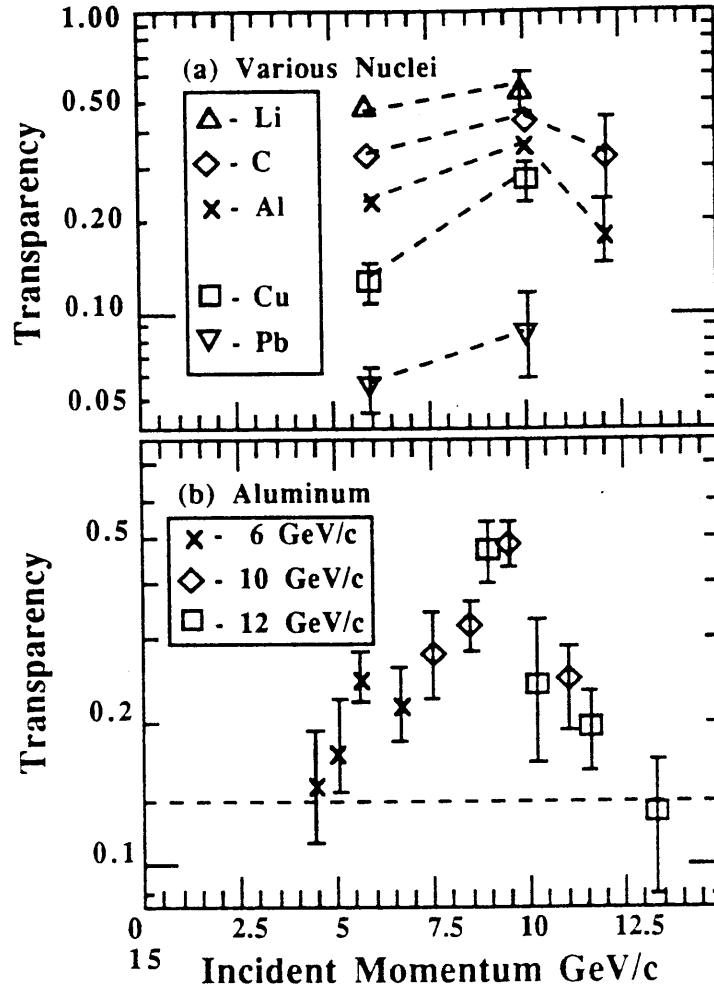


Fig. 1 - (a) The transparency vs beam momentum for various nuclear targets; (b) the transparency of aluminum target plotted vs effective incident momentum. The growing up to 10 GeV/c is in agreement with PQCD. The dotted horizontal line represents the energy-independent behaviour of the Glauber scheme.

A possible explanation of the anomalies observed both in the energy dependence of the absorptive corrections in nuclear targets, and, in the same kinematical region, in spin-spin correlation, has been given by Brodsky and de Teramond²². According to these authors, these results, which contradict the expectations of PQCD, can be explained if the scattering at the critical value $P_{lab} = 12$ GeV/c ($\sqrt{s} = 4.93$ GeV) is dominated by an s-channel $B = 2$ structure with mass near 5 GeV. Moreover, if this resonance has spin $S = 1$, it can also explain the large spin-spin correlation A_{NN} measured at $P_{lab} = 11.75$ GeV/c. Conversely, below 10 GeV/c, the perturbative hard-scattering amplitude is dominant at large angle and thus PQCD, and specifically color transparency, is satisfactorily in agreement with experiment.

Now, the threshold for open charm production

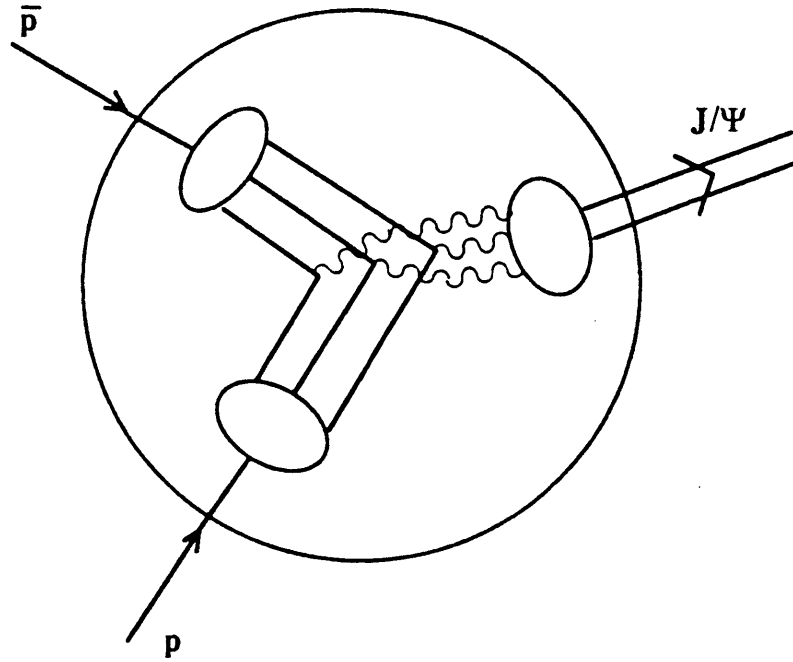


Fig. 2 - The annihilation of three antiquarks and three quarks into three gluons giving a J/Ψ

If the J/Ψ is produced near the resonance energy from the elementary reaction



it has non-relativistic velocities and is formed inside the nucleus. Thus QCD predicts that $\bar{p}p$ annihilation into charmonium, unlike usual annihilations, is not restricted to the front surface of the nucleus, but, on the contrary, occurs inside.

This fact has two important consequences. First, the $\bar{p}A$ production cross section is scaled additively from the elementary process

$$\bar{p}A \rightarrow J/\Psi \quad (A-1)^* \simeq Z(\bar{p}p \rightarrow J/\Psi) \quad (3)$$

according to the color transparency effect, based on the absence of initial- and final-state interactions.

The second consequence is that the study of the Z -dependence of the exclusive reaction can be used to determine the J/Ψ -nucleon cross section at low energy. Indeed, (3) is strictly valid if color transparency is active and, moreover, the J/Ψ -nucleon cross section is small.

The existing values of the J/Ψ -nucleon cross section have been obtained by analyzing J/Ψ production in nuclear targets both by incident photons and by incident hadrons^{24,25,26,27}.

The conclusion reached is that $\sigma(J/\Psi, N) \simeq 1 - 2$ mb. This information has become especially interesting recently, because of the suggestion²⁸ that J/Ψ suppression in heavy ion collisions might be a signature of quark-gluon plasma formation. Obviously, a crucial ingredient for drawing any

conclusion is the evaluation of the interaction cross section of J/Ψ in nuclear matter, which can hide the suppression due to the phase transition.

In order to extract the J/Ψ cross section in a nucleus from incoherent production data, one uses the following formula²⁹:

$$A_{\text{eff}} = \int_0^R 2\pi r dr \rho_0 \int_{-\sqrt{R^2-r^2}}^{+\sqrt{R^2-r^2}} dz \exp[-\sigma (\sqrt{R^2-r^2}-z) \rho_0] \quad (4)$$

where r is the impact parameter and z the longitudinal coordinate of J/Ψ with respect to the centre of the nucleus, ρ_0 is the nuclear density $= A^{4/3} \pi R^3$ for a large nucleus. From measuring A_{eff} one gets the cross section σ , which turns out to be $\approx 1 - 2$ mb, the value currently adopted to evaluate J/Ψ effective suppression in ion-ion interaction.

However, the $\sigma(J/\Psi, N)$ extracted using (4) presumably has little to do with J/Ψ scattering on a nucleon. We shall discuss this point, from which it will appear clearly the unique role that, conversely, can play a measurement performed using incident antiprotons.

Two essential assumptions are underlying formula (4):

- (i) the $(c\bar{c})$ partonic system is created in a locally identified position in z ;
- (ii) the J/Ψ becomes a physical particle immediately after the creation of the $c\bar{c}$ pair.

We want to check if these assumptions are reliable. Let us consider explicitly the quasi-elastic J/Ψ production by photons (electrons). As usually, in processes involving hard interactions, it is convenient to consider two separate time scales: a production time τ_p and a formation time τ_f . τ_p is the time scale over which the hard interaction occurs. τ_f is the time it takes the produced partonic system $\bar{Q}Q$ to separate to a transverse size comparable to the radius of the final state hadron. If there is no hard interaction, the distinction between τ_p and τ_f is lost. For hard interactions, at times less than τ_f one must deal explicitly with the partonic system. Only after τ_f it makes sense to talk of a particular hadron as existing. τ_p and τ_f are defined in a laboratory system having the target, nucleon or nucleus, at rest.

To leading order in the heavy quark mass the photon couples directly to the heavy quark. The production time τ_p for the partonic $(c\bar{c})$ -system turns out, from the Heisenberg principle, in the reference frame of $(c\bar{c})$

$$\tau_p^0 \approx 1/M \quad (5)$$

where M is the $(c\bar{c})$ -system mass. In the laboratory system, one has

$$\tau_p = \gamma \tau_p^0 \quad (6)$$

where γ is the Lorentz factor $= P/M$, P being the $(c\bar{c})$ momentum.

If the charmonium system carries most of the momentum of the incoming photon, P_γ^{30} , one finally has

$$\tau_p \simeq \frac{1}{M} \frac{P_\gamma}{M} \quad (7)$$

This relation means that also at high energy ($P_\gamma \simeq 100$ GeV) τ_p is still quite short, $\tau_p \simeq 10$ GeV⁻¹ $\simeq 2$ fm, or, equivalently, that the production of the ($c\bar{c}$)-system is local with respect the granularity of a nucleus. Thus, the assumption (i), for incoming energies of less than about 100 GeV, is fulfilled. However, the assumption (ii) is simply not correct.

After the production time τ_p , the ($c\bar{c}$)-system suffers a rather hard collision allowing the pair ultimately to become a J/Ψ . The formation time τ_F required for the ($c\bar{c}$) to separate to a transverse size comparable to the radius of the J/Ψ obey the relation

$$v_\perp \tau_F = r_{J/\Psi} \quad (8)$$

One can estimate $r_{J/\Psi} \simeq 0.5$ fm; v_\perp is the transverse velocity of a charmed quark in the J/Ψ : $v_\perp = p_\perp/E = p_\perp/P_\gamma$ where $p_\perp \simeq 0.5$ GeV.

Thus finally one can write

$$\tau_F \simeq 1 \text{ fm} \cdot P_\gamma \text{ (GeV)} \quad (9)$$

Therefore, even for $P_\gamma = 10$ GeV, this formation time is such that the J/Ψ state is produced *outside* the nucleus. What passes through the nucleus is *not* a normal J/Ψ and hence, the cross section extracted using the expression (4) presumably represents the scattering of the ($c\bar{c}$)-system with a nucleon instead of a hadron-nucleon interaction. Hence again, when evaluating the amount of suppression due to quark-gluon plasma formation, and the amount which is simply consequence of nuclear absorption, one actually has no elements to draw a definite conclusion.

Conversely, if J/Ψ production occurs by antiproton annihilation, QCD predictions about charmonium formation fully satisfy the conditions for the interaction of the physical J/Ψ with nucleons. Deviation from QCD transparency should allow to determine in an unambiguous way the effective - presumably weak - interaction cross section of charmonium with nucleons in nuclei.

4. - Experimental rates for charmonium production in nuclei by antiprotons

4.1 - Kinematics

In order to study color transparency in the production of the J/Ψ - or an other charmonium state denoted collectively by R below - in the quasi - exclusive reaction in nuclei

$$\bar{p}A \rightarrow R (A-1)^* \quad (1)$$

the antiproton beam energy must be near the resonance energy for the elementary reaction

$$\bar{p}p \rightarrow R \quad (2)$$

One then has, for the threshold values:

$$E_p^R = (E_{\bar{p}})_{thr} = \frac{1}{m_N} \left(\frac{M_R^2}{2} - m_N^2 \right) \quad (3)$$

$$P_p^R = (P_{\bar{p}})_{thr} = \sqrt{\frac{M_R^2}{4m_N^2} (M_R^2 - 4m_N^2)} \quad (4)$$

$$= \left(\frac{M_R}{m_N} \right) (P_{\bar{p}})_{c.m.} \quad (4')$$

where $(P_{\bar{p}})_{c.m.} = \frac{1}{2} \sqrt{M_R^2 - 4m_N^2}$ with obvious meaning of symbols. In Table I energy and momentum threshold values for charmonium are reported.

Table I

Threshold energy and momentum for charmonium production

Charmonium state (GeV)	P_p^R (GeV/c)	E_p^R (GeV)	$(P_{\bar{p}})_{c.m.}$ (GeV/c)
η_c (2.980)	3.67	3.79	1.16
J/Ψ (3.097)	4.07	4.17	1.23
χ_{c0} (3.410)	5.19	5.28	1.43
χ_{c1} (3.510)	5.55	5.63	1.48
χ_{c2} (3.555)	5.72	5.80	1.51
ψ' (3.685)	6.22	6.30	1.58
ψ (3.770)	6.57	6.64	1.63

4.2 - Mass spread in charmonium production from Hydrogen

The spread in mass in charmonium production from elementary process

$$\bar{p}p \rightarrow R \quad (1)$$

depends essentially on the beam resolution:

$$(\Delta M)_{\text{beam}}^R \cong \frac{m_N \Delta E_{\text{beam}}}{M_R} \quad (2)$$

If the momentum beam resolution is of the order of that of LEAR³¹

$$\Delta p/p \simeq 10^{-4} \quad (3)$$

one gets:

$$(\Delta M)_{\text{beam}}^R \cong 300 \text{ KeV} \quad (4)$$

4.3 - Mass spread in charmonium production in nuclei

In producing a resonance in nuclear matter, Fermi motion of nucleons plays a major role and dramatically smears the resonance width.

One has:

$$(\Delta M)_F^R \cong \frac{E_p^R}{M_R} k_F \quad (1)$$

where k_F is the Fermi momentum and thus:

$$(\Delta M)_F^R \cong 300 \text{ MeV} \quad (2)$$

4.4 - Cross section for charmonium production in nuclei

The cross section for the production of a charmonium state R in a $\bar{p}p$ annihilation occurring in nuclear matter, can be written

$$(\sigma_{\bar{p}p}^R)_A = \frac{1}{\Delta M_F} \int_{M_R - \frac{\Delta M_F}{2}}^{M_R + \frac{\Delta M_F}{2}} \sigma_{\bar{p}p}^R(M) dM \quad (1)$$

where $\sigma_{\bar{p}p}^R(M)$ is given by the usual Breit-Wigner cross section for resonance production:

$$\sigma_{\bar{p}p}^R(M) = \frac{(2J_R + 1)}{4} \frac{\pi}{(P_{\bar{p}})_{\text{cm}}^2} \frac{(\text{B.r.})_{\bar{p}p} (\text{B.r.})_{\text{out}} \Gamma_R^2}{(M - M_R)^2 + \frac{\Gamma_R^2}{4}} \quad (2)$$

After integration, one gets

$$(\sigma_{\bar{p}p}^R)_A = \frac{\Gamma_R}{\Delta M_F} \text{arctg} \left(\frac{\Delta M_F}{\Gamma_R} \right) \sigma_{\bar{p}p}^R \quad (3)$$

where $\sigma_{\bar{p}p}^R$ is the production cross section at the resonance

$$\sigma_{pp}^R = (2J_R + 1) \frac{\pi}{(P_p^-)_{cm}^2} (B.r.)_{pp}^- (B.r.)_{out} \quad (4)$$

If

$$\Delta M_F \gg \Gamma_R \quad (5)$$

$$\frac{\Gamma_R}{\Delta M_F} \arctg \left(\frac{\Delta M_F}{\Gamma_R} \right) \simeq \frac{\pi}{2} \frac{\Gamma_R}{\Delta M_F} \equiv S_R \quad \text{suppression factor.} \quad (6)$$

Then one can finally obtain:

$$(\sigma_{pp}^-)_A^R = \sigma_{pp}^R \cdot S_R \quad (7)$$

The dramatic suppressions of cross section due to Fermi smearing are reported in Table II.

Table II
Fermi smearing suppression in charmonium production in nuclei

Charmonium state (GeV)	E_p^- (GeV)	Γ_{tot} (MeV)	ΔM_F (MeV)	S_R
η_c (2.980)	3.79	10.3 + 3.8 -3.4	250	$6.5 \cdot 10^{-2}$
J/Ψ (3.097)	4.17	0.068 ± 0.010	270	$3.9 \cdot 10^{-4}$
χ_{c0} (3.415)	5.28	13.5 ± 5.3	310	$6.8 \cdot 10^{-2}$
χ_{c1} (3.510)	5.63	<1.3	320	$6.4 \cdot 10^{-3}$
χ_{c2} (3.555)	5.80	2.6 +1.2 -0.9	325	$1.2 \cdot 10^{-2}$
ψ (3.685)	6.30	0.243 ± 0.043	340	$1.1 \cdot 10^{-3}$

The calculated cross sections for charmonium production in nuclei are reported in Table III. For the J/Ψ , the leptonic channel is considered. For the χ state and the $\Psi(3.685)$ is taken into account the decay into J/Ψ .

Table III
Cross sections for charmonium production in nuclei

Charmonium state (GeV)	B.r. $\bar{p}p$	B.r. $\rightarrow J/\Psi$	B.r. $J/\Psi \rightarrow e^+e^-$	$\sigma_{\bar{p}p}^R$ (nb)	S_R	$(\sigma_{\bar{p}p}^R)_A$ (nb)
J/Ψ	$2.2 \cdot 10^{-3}$	1	$6.9 \cdot 10^{-2}$	400	$3.9 \cdot 10^{-4}$	0.16
$\chi_{c2}(3.555)$ $\rightarrow \gamma J/\Psi$	10^{-4}	$13.5 \cdot 10^{-2}$	" "	2.5	$1.2 \cdot 10^{-2}$	0.03
$\Psi(3.685)$ $\rightarrow \pi\pi J/\Psi$	$1.9 \cdot 10^{-4}$	$50 \cdot 10^{-2}$	" "	10	$1.1 \cdot 10^{-3}$	0.01

4.5 - Rates for charmonium production in nuclei at SuperLEAR

The events rate for charmonium production in nuclei is given by:

$$N_{ev}^R = L \cdot (\sigma_{\bar{p}p}^R)_A \cdot Z \cdot T \cdot \varepsilon \quad (1)$$

where L is the machine luminosity

$(\sigma_{\bar{p}p}^R)_A$ is the charmonium cross section in nuclei

Z is the proton number of the nuclear target

T is the nuclear transparency

ε is the fraction of solid angle covered by the detector.

Assuming the project luminosity of SuperLEAR³²

$L = 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ and, moreover,

$Z=20 \quad T=0.5 \quad \varepsilon=0.5$

with the cross section values given in the Table III, one gets the counting rates reported in Table IV

Table IV

Rates for charmonium production in nuclei by antiprotons

Charmonium state (GeV)	$(\sigma_{\bar{p}p})_A^R$ (nb)	N_{ev}^R
J/ψ (3.097)	0.16	0.08 ev/s \approx 300 ev/h
χ_{c2} (3.555)	0.03	0.015 ev/s \approx 50 ev/h
ψ (3.685)	0.01	0.005 ev/s \approx 18 ev/h

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