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CHARMONIUM HADROPRODUCTION ON NUCLEI AT ACCELERATOR ENERGIES

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The problem of theoretical description of processes $hA \to c\bar{c}X$ seems to be highly urgent in view of the new stage of experimental investigations of such processes [1-3] . In the cited experiments there was observed a decrease in the ratio

$$R(A/H) = \frac{\sigma(hA \to J/\psi X)}{A\sigma(hp \to J/\psi X)} \qquad (1)$$

with increasing A - atomic number of the target nucleus. To the approximation $\sigma(hA \to J/\psi X) \simeq \sigma(hN \to J/\psi X) \cdot A^{\alpha}$ there correspond values $\alpha < 1$, whereas for the Drell-Yan continuum ($M_{\mu^+\mu^-} > 4$ GeV) $\alpha_{DY} \simeq 1$ [1,4] .

The phenomenological approaches [5-7] suggested in the recent years to explain this phenomenon are not, to our mind, grounded enough, since they ignore interactions of the incident hadron h in nuclear matter right up to the moment of $c\bar{c}$ pair production. It is done, apparently, simply by analogy with the processes of Drell-Yan type, $hA \to \mu^+\mu^- X$. However such an analogy may hardly be considered correct because of, generally speaking, different nature of these two processes. On the background of the neglect of the primary hadron interactions the attempts of the authors [5-7] to explain the A-dependence of

$hA \to J/\Psi X$ cross sections only by introduced nonzero absorptive component σ^{Ψ}_{abs} seem to be illegitimate. Correspondingly, the estimates of J/Ψ formation time and of values of σ^{Ψ}_{abs} given in the mentioned works may have no relation to a real picture.

It is no less essential that the model with zero cross section of the initial hadron with account of only one inelastic act of interaction in the nucleus, $hN \to c\bar{c}X$, does not explain the observed [1,2,3,14] growth of exponents α with increasing $P_{\perp}$ of the registered state. As for the description of the series of experimental data on cross sections $\sigma(hA \to J/\Psi X)$, here in the presence of at least two free parameters, σ^{Ψ}_{abs} and τ_{Ψ}, it cannot be a serious argument in favour of such a model.

This also refers to a certain extent to the recent paper [18] wherein the incident hadron cross sections are taken into account (not quite correctly) only in the term that determines the contribution of initial states with intrinsic charm.

As will be seen further, the description of experimental data on $hA \to J/\Psi X$ is achievable in the approach including leading hadron multiple scattering, which neglects inelastic scattering and absorption cross sections of $c\bar{c}$ pair inside the nucleus.

In our study of processes on nuclei we will proceed from the simple model suggested earlier [8,9] whose most essential assumptions are as follows:

1. The soft processes of hN interaction include the stage of intermediate leading state (H) with the initial valence

composition, whose fragmentation length at energies of interest exceeds the size of nuclei.

2. The state H displays hadron-like properties in the nucleus and is capable of successive interactions with the cross section equal to that of the parent hadron h ($\sigma^{tot}_{HN} = \sigma^{tot}_{hN}$; $\frac{d\sigma^{hN \to HX}}{d^3p} = \frac{d\sigma^{HN \to HX}}{d^3p}$).

In the neglect of contribution of the hard processes to the total cross section of hN interaction the normalization condition for $h(H)N \to HX$ spectra is of the form

$$\int \frac{d\sigma^{h(H)N \to HX}}{dx} dx = \sigma^{tot}_{hN} \qquad (2)$$

since the summary probability of H decay in all channels equals unity. (The diffractive processes correspond to $H \equiv h$ or $H \equiv h^*$.)

Note that the approach based on the assumptions mentioned [8,9] has allowed to describe practically the entire set of FNAL data on inclusive spectra of the leading hadrons on nuclei at $0.3 \leqslant P_\perp \leqslant 7$ GeV/c [10] including the region with the "anomalous" ($\alpha > 1$) A-dependence.

As distinct from the leading hadrons which in the considered model are produced as a result of fragmentation of the leading cluster H , we assume that the $c\bar{c}$ pair production in the process $hA \to J/\Psi X$ occurs locally in the interaction of sea partons in one of the acts of collision of h or H with nucleus nucleons. (The models of gluon-gluon and $q\bar{q}$ -fusion [11] do not contradict such an approach.)

The absorption and inelstic scattering cross sections of $c\bar{c}$ pair in the nucleus are assumed zero. This may be both a result of large J/Ψ formation length [12] and a consequence of smallness of such cross sections for charmonium and charmed quarks proper.

So long as a detailed description of the processes at $x \to 1$ in the considered problem is inessential, for inclusive spectra we can use a simplified form:

$$\frac{d\sigma^{h(H)N\to HX}}{dx} = \frac{d\sigma_{nd}^{h(H)N\to HX}}{dx} + \sigma_{hN}^{d}\,\delta(x-1) \tag{3}$$

where $\frac{d\sigma_{nd}^{h(H)N\to HX}}{dx}$ are the spectra in the nondiffractive region; σ_{hN}^{d} is total cross section of the diffractive processes.

Under these assumptions the methods [13] of multiple scattering theory lead to the following expression for the inclusive cross sections of processes $hA \to J/\Psi X$:

$$\frac{d\sigma^{hA\to J/\Psi X}}{dx}(x,E) = \sum_{n=1}^{A} \tilde{N}_n(\sigma_{hN})\,\frac{d\sigma_{(n)}^{h\to J/\Psi}}{dx}(x,E)\ ;$$

$$\frac{d\sigma_{(1)}^{h\to J/\Psi}}{dx}(x,E) = \frac{d\sigma^{hN\to J/\Psi X}}{dx}(x,E)\ , \tag{4}$$

$$\frac{d\sigma_{(n)}^{h\to J/\Psi}}{dx}(x,E) = \frac{1}{\sigma_{hN}^{n-1}} \int \frac{d\sigma_{nd}^{hN\to HX}}{dx_1}(x_1)\ \frac{d\sigma_{nd}^{HN\to HX}}{dx_2}(x_2)\ \cdots \times$$

$$\times \frac{d\sigma^{HN\to J/\Psi X}}{dx_n}(x_n, x_1\ldots x_{n-1}E)\,\delta(x-x_1\ldots x_n)\,dx_1\ldots dx_n\ ,\quad n\geq 2$$

where

$$\tilde{N}_1(\sigma) = \frac{1}{\sigma}\int \left(1-\exp\{-\sigma T(\vec{b})\}\right) d^2 b\ ;$$

$$\tilde{N}_n(\sigma) = \tilde{N}_1(\sigma) - \sum_{i=1}^{n-1} N_i(\sigma) ;$$

$$N_i(\sigma) = \frac{1}{\sigma i!} \int (\sigma T(\vec{b}))^i \exp\{-\sigma T(\vec{b})\} d^2 b ;$$

$$T(\vec{b}) = \int \rho(\vec{b}, z) dz ;$$

$\rho(\vec{b}, z)$ is one-particle nuclear density; σ_{hN} is total cross section of nondiffractive hN -interaction; E is the energy of the incident hadron h .

The quantities $\frac{d\sigma_{(n)}^{h\to J(\Psi)}}{dx}$ represent differential cross sections of n-fold nondiffractive interaction with nucleus nucleons with $c\bar{c}$ -state produced in the final collision, whereas the factors $\tilde{N}_n(\sigma)$ determine the effective number of nucleons on which the mentioned act $h(H)N \to J/\Psi X$ occurs. (We assume that Feynman scaling is fulfilled in processes $HN \to HX$.)

In the model adopted the spectra of processes $hN \to J/\Psi X$ and $HN \to J/\Psi X$ must not differ substantially from each other, so we will assume $\frac{d\sigma^{hN\to J/\Psi X}}{dx} = \frac{d\sigma^{HN\to J/\Psi X}}{dx}$.

If these quantities would not have been dependent on energy E of the incident hadron, then the integration of the cross section (4) over variable x would have led to the equality $\sigma_{int}^{hA\to J/\Psi X} \simeq A\sigma_{int}^{hN\to J/\Psi X}$ (because $\sum_n \tilde{N}_n(\sigma) \equiv A$). This is a direct consequence of the smallness of the absorptive component in cross sections σ_{HN}^{tot} , which is reflected in the normalization condition (2). Actually, $\sigma_{int}^{hN\to J/\Psi X}$ is a quantity growing with energy, and $\sigma_{int}^{hA\to J/\Psi X}(E) =$ $= A\sigma_{int}^{hN\to J/\Psi X}(\bar{E}) < A\sigma_{int}^{hN\to J/\Psi X}(E)$, since the mean energy $\bar{E}$ in the act of production of J/Ψ is, generally speaking, lower than the initial energy E because of the inelastic collisions in the nucleus preceding the act $HN \to J/\Psi X$. Such a dependence reflects in general outline the experimentally observed behavior of cross sections [1,2,14] .

Of course, in the determination of the cross sections one must correctly take into account the kinematics of the processes and in particular the difference between the values of variables $x \equiv x_{lab}$ and x_F (which is especially essential at large masses of detected states). However, at sufficiently high energies this, as a rule, does not result in significant changes in the A-dependence of the processes.

In calculations for cross sections $\frac{d\sigma_{nd}^{h(H)N\to HX}}{dx}$ we used the same power parametrization as in Ref. [9] , $\frac{d\sigma_{nd}^{h(H)N\to HX}}{dx} = \sigma_{hN}\, x^{\nu}(\nu+1)$; in this case the indices $\nu = (2K_H^{el}-1)/(1-K_H^{el})$ were fixed by the values of elasticity coefficients K_H^{el} in the relevant processes found when describing inclusive spectra $hA \to hX$ [9] ($K_{Hp}^{el} = 0.65$; $K_{H\pi}^{el} = 0.63$).

In the parametrization of spectra $h(H)N \to J/\Psi X$ $(h \equiv p, \pi)$ we used the factorized form

$$\frac{d\sigma^{h(H)N\to J/\Psi X}}{dx_F}(x_F, E) = a(1-x_F)^{b} F(E)\,, \qquad x_F > 0 \tag{5}$$

where parameters a and b were determined by fitting of experimental points [14] on processes $hp \to J/\Psi X$. As for the form of $F(E)$, here for $E \leqslant 300$ GeV there was taken the dependence $F(E) \sim (1-C/\sqrt{E})\,\theta(\sqrt{E}-C)$, C = 6 (GeV)$^{-1/2}$ [15] that describes the energy behavior of total cross sections for processes $pN \to J/\Psi X$ and $\pi N \to J/\Psi X$ up to E = 40 GeV. As it follows from (5), we assumed that spectra $hN \to J/\Psi X$ have the same form for the free and nucleus nucleons.

The effective nucleon numbers $\tilde{N}(\sigma_{hN})$ in (4) were calculated in the Fermi model with parameters taken from [16] .

Following expression (4) we determined integral cross sections

$$\sigma_{int}^{hA \to J/\Psi X}(E) = \int_0^1 \frac{d\sigma^{hA \to J/\Psi X}}{dx_F}(x_F, E)\,dx_F \qquad (6)$$

as well as relations of the form

$$R_{A_1/A_2} = \frac{\sigma^{hA_1 \to J/\Psi X}}{A_1} \Big/ \frac{\sigma^{hA_2 \to J/\Psi X}}{A_2} \qquad (7)$$

for the differential and integral cross sections.

Let us dwell first on the description of processes $\pi^- A \to J/\Psi X$ [2,3,14] .

In NA3 Collaboration [14] they have measured integral cross sections (6) (with account of decay probability $B(\Psi \to \mu^+ \mu^-)$) on hydrogen and platinum nuclei at incident pion energies E_{π^-} = 150, 200 and 280 GeV.

In the calculations performed for normalization of cross sections of $\pi^- Pt \to J/\Psi X$ there was used the quantity $B \cdot \sigma_{int}^{\pi^- p \to J/\Psi X}$ = 6.5 nb [14] at E_{π^-}= 150 GeV. (Note that the utilized dependence $F(E)$ [15] quite correctly describes data [14] on cross sections $\sigma_{int}(\pi^- p \to J/\Psi X)$ at above-cited energies.)

Fig.1 shows the curve obtained for cross sections $B \cdot \sigma_{int}^{\pi^- pt \to J/\Psi X}$ together with experimental data [14] at various energies E_{π^-} .

An agreement with results [14] on inclusive spectra $\frac{d\sigma^{\pi^- Pt \to J/\psi X}}{dx}$ is achieved too. This can be seen from Fig.2 wherein we have given as an example the calculated and experimental data for the quantity $1/R_{Pt/H}(x_F) = 195 \frac{d\sigma^{\pi^- p \to J/\psi X}}{dx_F}$ / / $\frac{d\sigma^{\pi^- Pt \to J/\psi X}}{dx_F}$ at the energy E_{π^-}= 280 GeV.

Note that some typical deviation of the curves $1/R_{Pt/H}(x_F)$ from the experimental points [14] at $x_F \lesssim 0.1$ is observed at energies E_{π^-}= 150 and 200 GeV too. Such a tendency at $x_F \to 0$ may indicate the increase of contributions to the cross sections of $hN \to c\bar{c}X$ mechanisms connected with the fragmentation of the leading H states.

In E-537 experiment [2] the processes $\pi^- A \to J/\psi X$ (A ≡ Be, Cu, W) were studied at E_{π^-} = 125 GeV. To avoid a wide corridor for curves in the description of results [2] (since $B(\psi \to \mu^+\mu^-)$ = = 7.4 ± 1.2% [14]), the normalization of cross sections (6) here was chosen according to the mean experimental point for a berillium nucleus.

Fig.3 presents a found A-dependence of cross sections $\sigma_{int}^{\pi^- A \to J/\psi X}$ at E_{π^-}= 125 GeV, and Fig.4 - results of calculated ratios $R_{W/Be}(x_F)$ for differential cross sections together with the corresponding data [2] .

Finally, in the recent E-672 experiment [3] the similar processes have been studied on C, Al, Cu and Pb nuclei at initial energies E_{π^-}= 530 GeV. The main result of Ref. [3] is the determination of the A-dependence of quantities

$$\sigma^{\pi^- A \to J/\psi X}(x_{F_1}; x_{F_2})/A = \frac{1}{A} \int_{x_{F_1}}^{x_{F_2}} \frac{d\sigma^{\pi^- A \to J/\psi X}}{dx_F} dx_F \qquad (8)$$

at $x_{F_1} = 0.1$ and 0.2; $x_{F_2} = 0.8$.

In the present paper, in view of lack of confident data on cross sections of $\pi^- N \to J/\psi X$ at $E_{\pi^-} = 530$ GeV, the dependence $F(E)$ [15] in integration was extrapolated for the entire region $E \leqslant 530$ GeV, and quantities (8) proper were normalized in accordance with experimental values [3] for a carbon nucleus.

Calculated results as well as data [3] on cross sections (8) are given in Fig.5.

We emphasize that the quantitative description of processes $\pi^- A \to J/\psi X$ was achieved in the used model practically with not a single fitting parameter, using only experimentally fixed quantities for normalizations.

The similar method was used in calculations of processes $pA \to J/\psi X$ [1] ($E_p = 800$ GeV, A ≡ C, Ca, Fe, W). Function $F(E)$ in (5) in this case was given in the range 300 GeV < < E $\leqslant$ 800 GeV by a linear form that provided the required factor of the cross section growth $\gamma = \sigma^{pp \to c\bar{c}X}$ (800 GeV) / / $\sigma^{pp \to c\bar{c}X}$ (400 GeV). (According to LEBC data [17] , $\gamma = 1.7^{+0.6}_{-0.5}$.)

As shown by calculations, a satisfactory agreement with the E-772 data [1] on A-dependence of J/ψ production cross section is attainable only for values of γ near the lower limit of the range [17] . At a more rapid growth of $\sigma^{pp \to c\bar{c}X}$ with energy the theoretical curves lie somewhat lower than experimental points [1] .

Fig.6 presents as an example the data on differential cross section ratios $R_{A/H}(x_F)$ for C and W nuclei. The curves are obtained assuming $\gamma = 1.2$.

The possible underestimation of cross sections of $pA \to J/\Psi X$ in the applied model may be due to the contribution of the two-step channels of the type of $p \to \pi \to J/\Psi$ *). (Detailed analysis of such transitions is rather complicated, being hardly reasonable until more accurate data on γ appear.)

Now we will summarize the main conclusions that follow from the performed study of charmonium hadroproduction on nuclei:

- Under the accuracy of experimental data available at present there are no reasons to assume that the cross section of $c\bar{c}$ pair absorbtion in nuclear matter and the cross section of $c\bar{c}$ inelastic scattering on nucleus nucleons differ substantially from zero.

- The decrease in the ratio $R(A/H)$ with increasing A is essentially due to the growth of cross sections $\sigma^{hN \to J/\Psi X}$ with incident hadron energy.

- The distortion of structure functions of sea partons for nucleus nucleons does not affect noticeably the cross sections of $c\bar{c}$ hadroproduction on nuclei.

It should also be mentioned that, to our mind, the so-called "diffractive" component [14] of J/Ψ hadroproduction is not due to the "new production mechanism of the J/Ψ " **), but

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*) In the usual multiple scattering model [15] the account of them leads to the correction $\simeq$ 20-40%.

**) which is connected, to the opinion of authors of [18] , with the intrinsic charm in the incident hadron wave function.

simply corresponds to the first term of expansion (4) ($= \tilde{N}_1(\sigma_{hN}) \frac{d\sigma^{hN \to J/\psi X}}{dx}$) that implies the $c\bar{c}$ production in the first nondiffractive act of collision in the nucleus ($\tilde{N}_1(\sigma_{pN}) \sim A^{0.74}$; $\tilde{N}_1(\sigma_{\pi N}) \sim A^{0.79}$).

The processes of charmed particle hadroproduction on nuclei, $hA \to h_c(h_{\bar{c}})X$, can be considered in a similar way. However, this subject is beyond the scope of our paper.

Against the background of the successful description of processes $hA \to c\bar{c}X$ the situation with the processes of Drell-Yan type may seem paradoxical. Note, however, that the "transparency" of nuclei for the Drell-Yan continuum ($M_{\mu^+\mu^-} \gtrsim 4$ GeV) is, generally speaking, relative. So, the data [1,4] on decreasing $R^{DY}_{A/H}$ with increasing x_F and growing α_{DY} with registered transverse momentum of $\mu^+\mu^-$ pair point out repeated interactions in the nucleus of the states with certain cross section and spectra.

The principal distinction between the Drell-Yan processes and the processes of $c\bar{c}$ hadroproduction consists in direct participation in interaction of the valence component of the incident hadron h . At $x_F > 0$ the processes of annihilation of one of the valence quarks (antiquarks) with a sea parton of the target would have to dominate in the inclusive spectra $\frac{d\sigma^{hN \to \mu^+\mu^- X}}{dx}$. Correspondingly, the hard structure functions of valence quarks would have led to a substantial growth of these spectra, especially at $x_F \lesssim 1$.

Let us imagine the state vector of hadron h at a time instant that precedes the interaction with the nucleus in the form of a superposition of state vectors with different momentum share carried by sea partons. The main contribution to the observed cross sections of the Drell-Yan processes must correspond to states with relatively hard valence and soft sea components. However, such states in interaction with nucleus nucleons will have the elasticity coefficient higher than the mean hadron state has, and, generally speaking, a lower non-diffractive cross section. Both these factors in expressions similar to (4) lead to the growth in α exponents in the A-dependence of inclusive spectra.

A detailed discussion of the Drell-Yan processes on nuclei will be given elsewhere.

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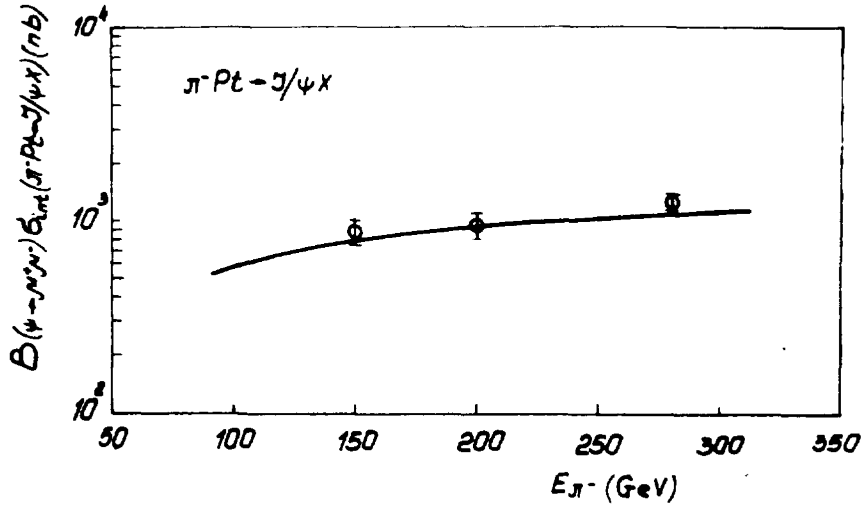

$\pi^- Pt \to J/\psi X$
10^4
10^3
10^2
50
100
150
200
250
300
350
E_{π^-} (GeV)

Fig.1

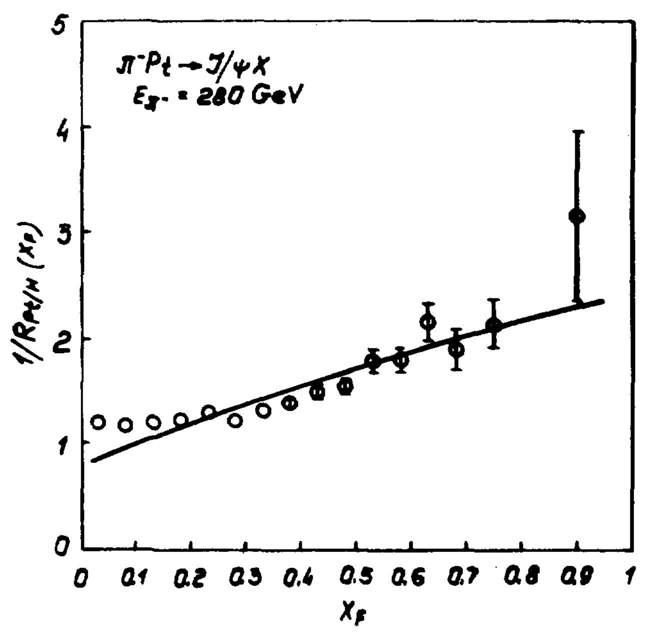

$\pi^- Pt \to J/\psi X$
$E_{\pi^-} = 280$ GeV
$1/R_{Pt/H}(x_F)$
0
1
2
3
4
5
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
X_F

Fig.2

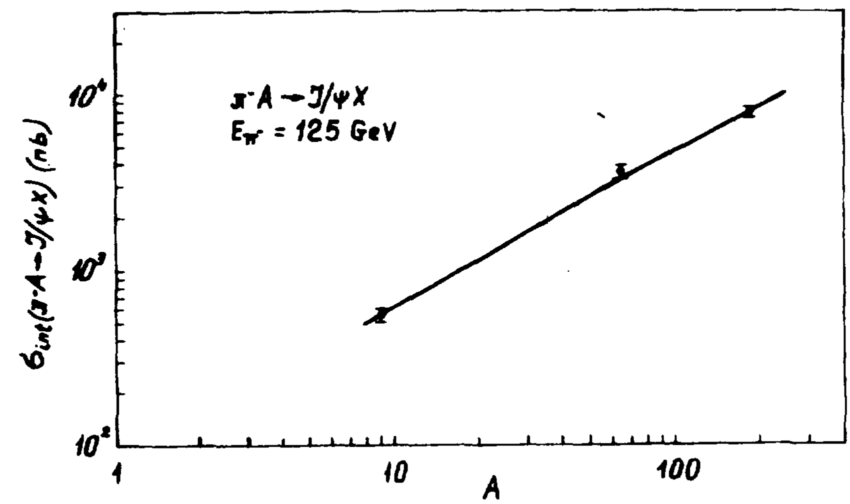

$\pi^- A \to J/\psi X$
E_{π^-} = 125 GeV
$\sigma_{int}(\pi^- A \to J/\psi X)$ (nb)
A

Fig.3

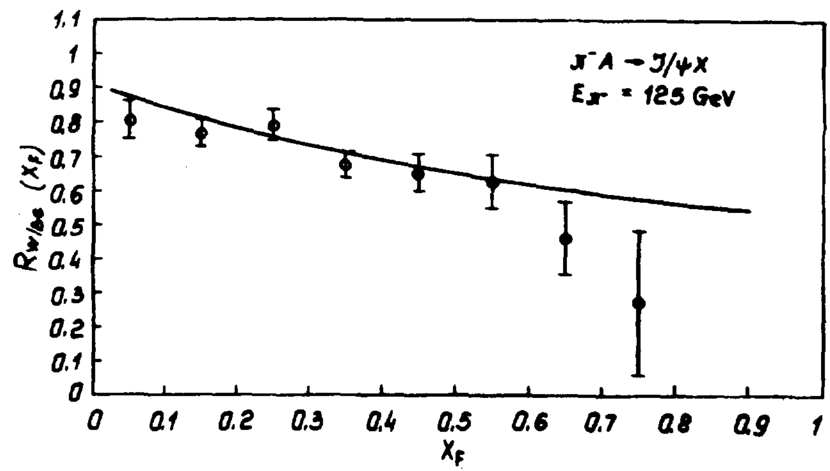
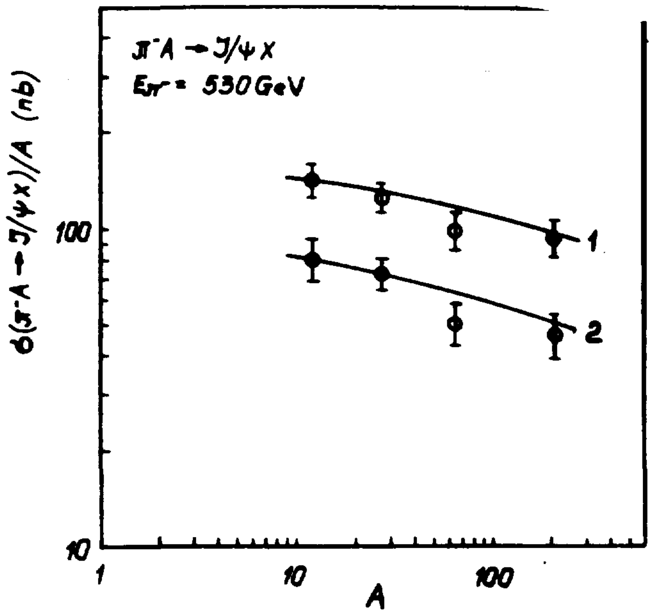
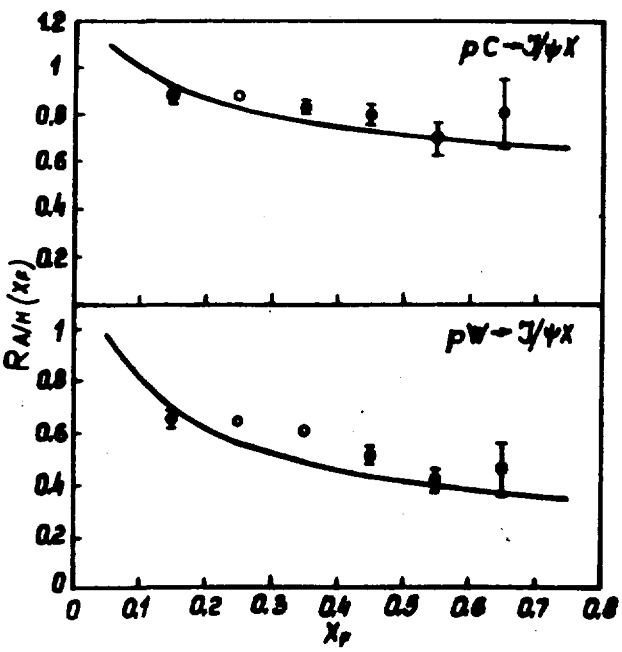

$\pi^- A \to J/\psi X$
E_{π^-} = 125 GeV
$R_{W/Be}$ (x_F)
x_F

Fig.4



$\pi^- A \to J/\psi X$
$E_\pi = 530$ GeV
$\sigma(\pi^- A \to J/\psi X)/A$ (nb)
100
10
1
10
100
A
1
2

Fig.5



pC→J/ψX
pW→J/ψX
$R_{A/H}(x_F)$
1.2
1
0.8
0.6
0.4
0.2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
X_F

Fig.6

F i g u r e   C a p t i o n s.

Fig.1. Calculated and experimental [14] values for the integrated ($X_F^{J/\psi} > 0$) cross sections of the process $\pi^- Pt \to J/\psi X$, $\hookrightarrow \mu^+ \mu^-$ at different energies of incident pions.

Fig.2. Quantities $1/R_{Pt/H}(x_F)$ for the process $\pi^- Pt \to J/\psi X$ at incident pion energy E_{π^-} = 280 GeV. Experimental data are taken from Ref. [14] .

Fig.3. A-dependence of integrated ($x_F > 0$) cross sections of processes $\pi^- A \to J/\psi X$ at incident pion energy E_{π^-} = 125 GeV. Experimental data are taken from Ref.[2]

Fig.4. Ratios $R_{W/Be}(x_F)$ for processes $\pi^- A \to J/\psi X$ at incident pion energy E_{π^-} = 125 GeV. Experimental data are taken from Ref. [2] .

Fig.5. A-dependence of quantities $\sigma^{\pi^- A \to J/\psi X}$ (0.1;0.8)/A (curve 1) and $\sigma^{\pi^- A \to J/\psi X}$ (0.2;0.8)/A (curve 2) at incident pion energy E_{π^-} = 530 GeV. Experimental data are taken from Ref. [3] .

Fig.6. Ratios $R_{A/H}(x_F)$ for processes $pA \to J/\psi X$ for C and W nuclei at incident proton energy E_p = = 800 GeV and γ = 1.2 in comparison with experimental data [1] .

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