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Properties of nuclear production of $J/\psi(3.097)$

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Cross sections of the inclusive reactions $\pi^- A$, $\bar{p}A$, and $\gamma A \to J/\psi + \cdots$ at $P_{\rm lab} \simeq 40$ and 125 GeV/c are investigated using the geometric model with the same A dependence as expected from the Fermi distribution of nuclear density. The fits agree well with the data. An overall fit to all four sets of data assuming a constant absorption mean free path and a power law for the energy dependence of the radius parameter indicates no anomaly of J/ψ production from the W and Pb targets. It is found that due to the threshold effect the temperature of J/ψ is much cooler than the π temperature. A remark is made on a similar formula for the cross section of the nucleus-nucleus reaction.

I. INTRODUCTION

It is well known that the investigation of nuclear production of J/ψ is, among other things, a challenge to test the QCD prediction that its cross section is suppressed in large nuclei due to the screening effect of the quark-gluon plasma.[1] Recently, from a Fermilab experiment (E537) of inclusive reactions $\bar{p}+A$ and $\pi^- + A \to J/\psi + \cdots$ at $P_{\rm lab} = 125$ GeV/c, Katsanevas *et al.* reported J/ψ suppression in the W target.[2] They used the power law of quark model $\sigma = \sigma_0 A^\alpha$ to analyze their data and found it inadequate (sic), as is seen from the downward curvature of the logarithmic plot of their data reproduced in Fig. 1. Clearly, this A dependence is different from that of another Fermilab experiment (E691), the photoproduction of J/ψ at about the same energy, 120 GeV by Sokoloff *et al.*[3] The logarithmic plot of their incoherent data is practically linear, see Fig. 2; they found $\alpha = 0.94 \pm 0.01$.

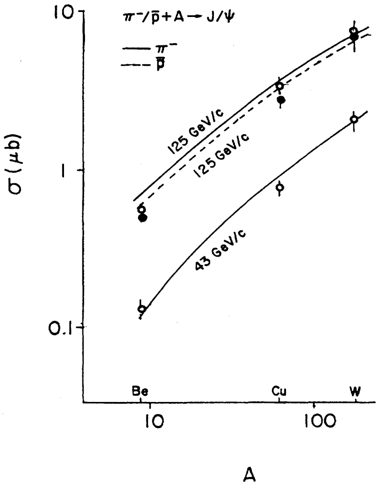

FIG. 1. Inclusive cross sections of J/ψ from hadron-nucleus reactions. Data from experiments of Fermilab E537 and Superkhov, Refs. 2 and 9. The curves represent the OM fit, Eq. (2); the parameters are listed in Table I.

We recall that this power law $\sigma \sim A^\alpha$ is equivalent to the Glauber theory[4] It may be derived from the optical-model (OM) formula,[5]

$$\sigma = \pi \int_0^R (1 - e^{-2\Omega(b)}) db^2 = \pi R^2 \left\{ 1 - 2 \left[1 - \left(1 + 2\frac{R}{\lambda} \right) e^{-2R/\lambda} \right] \left[\frac{\lambda}{2R} \right]^2 \right\}, \quad (1)$$

where R is the nuclear radius and $\Omega(b) = \sqrt{R^2 - b^2}/\lambda$ the eikonal, λ being the absorption mean free path (mfp). Note that for small λ, i.e., black nucleus, $\sigma \propto R^2$ and that for large λ, i.e., transparent nucleus, $\sigma \propto R^3$; therefore $\sigma \approx A^\alpha$ with $\frac{2}{3} \le \alpha \le 1$.

The purpose of this paper is to investigate the properties of J/ψ using an appropriate OM formula derived from (1) for the A dependence as well as for its energy dependence. We will also discuss the threshold effect on the temperature in order to get some insight into the production mechanism of J/ψ, especially its temperature compared to π production.

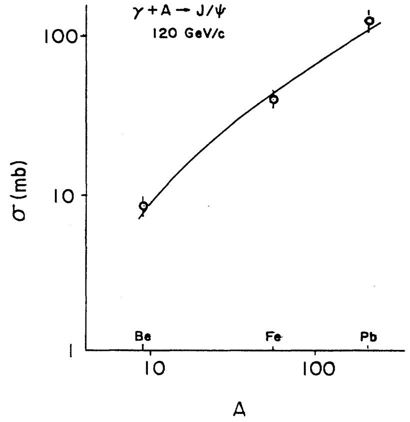

FIG. 2. Inclusive photoproduction of J/ψ of the Fermilab experiment E691, Ref. 3. The OM fit is shown by the curve; for parameters, see Table I. Note that the curvature of the logarithmic plot is less important as the absorption mfp is one-half of that of π-A, see text.

II. THE OM INCLUSIVE CROSS SECTION

Consider the optical-model cross section for the inclusive nuclear reaction

$$h + A \rightarrow X + \cdots \ .$$

Bearing in mind that the cross section is a geometrical concept, we may use the large-A approximation to rewrite (1) in the form of a square as

$$\sigma_{hX} = \pi r_{hX}^2 (A^{1/3} - a/A^{1/3})^2 \ , \tag{2a}$$

where

$$a = (\lambda_{hX}/2r_h)^2 \ . \tag{2b}$$

The two parameters are the radius parameter r_{hJ} and the absorption mfp λ_{hJ}, r_h being the radius parameter of the total absorption cross section corresponding to $R = r_h A^{1/3}$ in (1). Clearly, the parameters of partial cross sections are subject to the condition

$$r_h > r_{hX}, \quad 1/\lambda_h = \sum_X 1/\lambda_{hX} \ . \tag{3}$$

The important property of this formula is the following: the effective radius $\mathcal{R} = \sqrt{\sigma_{hX}/\pi}$ has the same A dependence as the rms radius of the Fermi distribution of nuclear density, as has been discussed elsewhere.[6] It follows that this formula (2) may be used for any partial cross section as well. Indeed, this type of cross section (2a) has also been found for the diffractive production of particles with this change for (2b), namely, $a \rightarrow \frac{1}{2}a$, as has been reported before.[7]

Thus we are led to use (2) to investigate the nuclear cross sections of J/ψ and compare the parameters with those of other reactions, especially the parameters (in fm) of total absorption cross sections σ_h for pA and πA of a previous work:[6] namely,

$$r_p = 1.30 \pm 0.01, \quad \lambda_p = 1.44 \pm 0.23 \ ,$$

$$r_\pi = 1.20 \pm 0.25, \quad \lambda_\pi = 2.40 \pm 0.27 \ .$$

It is worth noting that $\lambda_p \simeq 1/m_\pi$, whereas $\lambda_\pi / \lambda_p \simeq \frac{3}{2}$ as is expected from quark counting. As for the radius parameters, r_p / r_π is, within experimental errors, equal to the ratio of rms radii of the proton and the pion according to the elastic pp and πp scattering.[6]

Finally, our previous analysis of photoproduction of ρ using the accurate measurements of nuclear radii by the DESY-MIT Collaboration (Ref. 8) has given[6]

$$\mathrm{rms} r_\gamma = 1.14 \pm 0.01, \quad \lambda_{\gamma\rho} = 1.07 \pm 0.06 \ .$$

Note that this value of rmsr_γ agrees with 1.12±0.02 fm of their experiment and that here, $\lambda_{\gamma\rho} \sim \frac{1}{2}\lambda_\pi$ reflecting the vector-meson property: namely, $\gamma \rightarrow \rho^0 \rightarrow \pi^+ + \pi^-$ so that $1/\lambda_{\gamma\rho} = 1/\lambda_{\pi+} + 1/\lambda_{\pi-} = 2/\lambda_\pi$, as reported previously.[6]

III. NUCLEAR PRODUCTION OF J/ψ

We now proceed to fit the E537 data (Ref. 2) using the formula (2), then the Serpukhov data of $\pi^- + A \rightarrow J/\psi$ at $P_{\mathrm{lab}} = 48$ GeV/c (Ref. 9) and the incoherent photoproduction data of E691 (Ref. 3). The parameters of fit are listed in Table I and the fits are shown in Figs. 1 and 2; the agreement with data is very satisfactory.

Note that λ_{hJ}/r_h for the photoproduction is about one-half of that of $\bar{p}/\pi^- + A \rightarrow J/\psi$, so that the nuclear absorption described by the negative term $a/A^{1/3}$ in (2) is 4 times more important for $h + A$ than for $\gamma + A \rightarrow J/\psi$. This explains the difference in the logarithmic plot of σ vs A, i.e., more downward curvature for the hA than for the γA case.

In an attempt to further investigate the absorption property, we have analyzed the photoproduction of ϕ using the Cornell data (Ref. 10); the parameters of fit are listed in Table I. In addition, we have also used the ratio of cross sections on Be and Ta targets of ϕ production by p and π^+ at 120 GeV/c of CERN SPS experiment NA11 (Ref. 11) to estimate the absorption mfp. The values thus obtained are listed in Table I.

A comparison of the values of λ in Table I indicates that they are practically the same for J/ψ, ϕ, and ρ, and that λ of photoproduction is about one-half of that of π-nucleus cross section as mentioned before for $\gamma + A \rightarrow \rho$.

Finally, we note that the radius parameter of $\gamma + A \rightarrow J/\psi$ at 120 GeV/c is about $\sqrt{\alpha} = 1/\sqrt{137}$ times smaller than that of $\pi^- + A \rightarrow J/\psi$ at 125 GeV/c as expected from the electromagnetic interaction; therefore, by means of the substitution

TABLE I. Optical-model parameters of cross sections of inclusive reaction $h + A \rightarrow X + \cdots$.

P_{lab} (GeV/c)	Reaction	r_{hX} (mfp)	λ_{hX}/r_x	Ref. and note
125	$\bar{p}A \rightarrow J/\psi$	2.66±0.23	2.01±0.08	2
120	$pA \rightarrow \phi$		2.38±0.10	11[a]
125	$\pi^- A \rightarrow J/\psi$	2.87±0.17	2.17±0.06	2
120	$\pi^+ A \rightarrow \phi$		2.23±0.09	11[a]
43	$\pi^+ A \rightarrow J/\psi$	1.44±0.05	2.46±0.05	9
120	$\gamma A \rightarrow J/\psi$	0.33±0.01	1.07±0.06	3
8.3	$\gamma A \rightarrow \phi$	11.7±0.40	1.27±0.35	10
7.5	$\gamma A \rightarrow \rho^0$		0.94±0.12	8[b]

[a] Only two cross sections are available.

[b] The estimates of rms radius parameter are given in Sec. II. See also Ref. 8.

$$r_{\gamma J} \to r_{hJ}/\sqrt{\alpha}, \quad \lambda_{\gamma J} \to \lambda_{\pi J}/2 \tag{4}$$

the photoproduction may be treated together with the π-nucleus reaction.

IV. ENERGY DEPENDENCE OF J/ψ PRODUCTION

Consider next the radius parameters of (2) for J/ψ production listed in Table I. Its dependence on energy is obvious, since the other parameter a of (2) is practically constant.

In this respect, we note the rapid increase of r_{hJ} for $\pi^- + A \to J/\psi$ from $P_{\text{lab}} = 43$ to 125 GeV/c. Note also that the difference in the radius parameter between $\bar{p}A$ and $\pi^- A$ production of J/ψ at the same $P_{\text{lab}} = 125$ GeV/c is due to the mass difference of the projectile: namely, the available energy for J/ψ production (cf. *infra*) being $W^* = 3.70$ compared to 4.5 GeV for $\bar{p}A$ and $\pi^- A$ production, respectively.[12]

As the hypothesis of limiting fragmentation[13] holds also in the case of particle production by hadron-nucleus reactions,[14] we find the available energy for the projectile fragmentation as follows:

$$W_h^* = E_h^* - m_h - m_J , \tag{5}$$

where E_h^* denotes the projectile energy (in GeV) in the c.m. system (c.m.s.) (specified by an asterisk) of the incident hadron h and one nucleon of the target nucleus, the Fermi motion being neglected for simplicity. We assume

$$r_{hJ} = C(W_h^*/m_J)^{\alpha/2} \tag{6}$$

and find

$$C = 0.47 \pm 0.09 \text{ mfm}, \quad \alpha/2 = 0.73 \pm 0.10 .$$

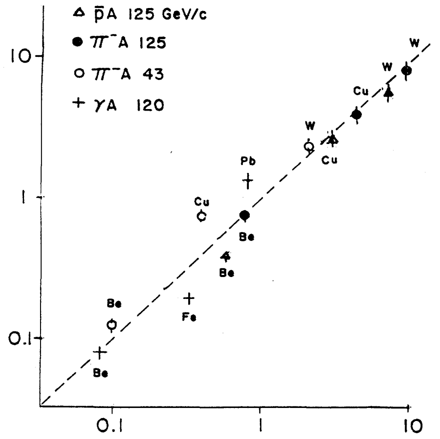

FIG. 3. Overall fit of J/ψ cross sections in Figs. 1 and 2, data of Fermilab and Superkhov experiments, Refs. 2, 3, and 9, assuming constant absorption mfp and a power law for the energy dependence of the radius parameter of the OM formula (2), see text.

We now use (2) and (6) to compute the cross sections for J/ψ production assuming $a = 1.00$ and 1.24 for $\bar{p}$-A and π^--A reactions, as listed in Table I, including the photoproduction in view of (4), for all 12 cross sections we are dealing with in the present work, see Figs. 1 and 2. The results are shown in the plot of Fig. 3 against the measured cross sections.

Comparing our computed σ_{hJ} with the data, we find an average deviation $\sim 16\%$. The agreement is rather satisfactory, partly because of our crude calculation, and partly because of large systematic errors involving three different and difficult experiments. We note especially that there is no anomaly in the case of large targets of W and Pb.

Finally, we note that for a given A, the cross section of J/ψ production rises as $\alpha \sim \frac{3}{2}$ power of the available energy, indicating rather a rapid rise up to $P_{\text{lab}} = 120$ GeV/c.

V. THE TEMPERATURE OF J/ψ

Because of the threshold effect, the temperature T_J of J/ψ production is expected to be, in general, lower than T_π of π production in the same reaction. Indeed, according to the statistical approach, *the temperature is zero at the threshold* and increases slowly with the incident energy, as has been observed in the case of T_π (Ref. 15). Thus arises the important question concerning the thermal equilibrium, which is a basic assumption of most statistical models of particle production.

Experimentally, from the Serpukhov data of $P_\perp$ distribution of J/ψ produced by $\pi^- + A$ at 43 GeV/c [Ref. 9(b)], we estimate $T_J = 78 \pm 11$, 110 ± 19, and 124 ± 28 MeV for Be, Cu, and W targets, respectively, whereas the CERN SPS experiment of $\pi^+ + p \to J/\psi$ at $P_{\text{lab}} = 39.5$ GeV/c (Ref. 16) gives $T_J = 123 \pm 10$ MeV. We note that these temperatures are significantly lower than $T_\pi \sim 140$ MeV for $\pi^+ p \to \pi^- + \cdots$ at $P_{\text{lab}} \sim 40$ GeV/c (Ref. 17); just as in the case of $\pi^+ + p \to J/\psi$ (Ref. 15), $T_J = 135 \pm 15$ MeV compared to $T_\pi \sim 155$ MeV, as reported previously.[18,19] Thus, compared to π, there is a cooling for J/ψ production from hadron-nucleus reactions. This property has actually been observed from the well-known DESY-MIT experiment of the discovery of J, indeed from their $P_\perp$ distribution,[19] it is found $T_J = 102$ MeV and $T_\pi = 130 \pm 5$ MeV as reported in Ref. 15.

VI. REMARKS

It should be noted that unlike the power law $\sigma = \sigma_0 A^\alpha$ which is often used to extract the cross section on a single nucleus $\sigma_0 = \sigma(A = 1)$, the OM formula (2), as is well known, is not applicable to the hydrogen target (Ref. 20).

As regards the cross section of nucleus-nucleus [heavy-ion (HI)] reactions, an OM formula similar to (2) has been presented some time ago, but remained unnoticed; it has been tested using the LBL Bevalac data (Ref. 6). It is

$$\sigma = \pi r^2 \left[A_1^{1/3} + A_2^{1/3} - \frac{c}{A_1^{1/3} + A_2^{1/3}} \right]^2 \tag{7a}$$

with

$$c=2(\lambda/r)^2 \tag{7b}$$

the subscripts being omitted for simplicity. Referring to (2b), we get $c/a=8=2^3$; that $c>a$ is due to more important rescattering of nucleons of A_1 and A_2 in collision.

The resemblance between (7a) and (2a) suggests that the HI cross section may be related to that of p nucleus by replacing:

$$A^{1/3}\rightarrow A_1^{1/3}+A_2^{1/3},\quad a\rightarrow 8a\ , \tag{8}$$

namely, superposing two nuclei A_1 and A_2, *without overlapping*. This formula may be regarded as an improvement of the well-known formula of Bradt and Peters,[21] the characteristic overlapping parameter being

$$b=\frac{c}{A_1^{1/2}+A_2^{1/3}} \tag{9}$$

decreasing with the nuclear size, as is well known experimentally,[6] so that the OM formula (7) is more accurate. Note that what is commonly considered as "overlapping" of HI reaction is actually an absorption effect which exists in p-nucleus reaction as the $a/A^{1/3}$ term.

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