HEAVY QUARKONIUM PRODUCTION AND PROPAGATION IN NUCLEI

Cheuk-Yin Wong

Physics Division, Oak Ridge National Laboratory*, Oak Ridge, TN 37831

Proceedings of

International Symposium on Trends in Subatomic Physics
Taipei, Taiwan
August 7-23, 1997

DISCLAIMER

Heavy Quarkonium Production and Propagation in Nuclei

Cheuk-Yin Wong[a]*

[a]Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831

We describe a precursor in heavy quarkonium production in terms of a coherent admixture of states of different color, spin, and angular momentum quantum numbers, and obtain the production amplitudes for different quarkonium bound states by projecting out this precursor state onto these bound states. The precursor is absorbed in its passage through a nucleus in a pA reaction, and the total cross section between this precursor with a nucleon can be calculated with the two-gluon model of the Pomeron. Such a description of coherent precursors and their subsequent interactions with nucleons can explain many salient features of J/ψ and ψ' production in pA collisions.

1. Introduction

It is a great pleasure to write this article in honor of Prof. Tai-You Wu's 90th Birthday. Prof. Wu's grandfather and father were respectively "Jin Shi" and "Ju Ren", which were among the highest honors a Chinese scholar could achieve in the last century. Prof. Wu himself was instrumental in bringing modern physics to China, and has trained a large number of physicists, including C. N. Yang and T. D. Lee. Through the lineage of Tai-You Wu, Chinese physics scholars of today are a part of the continuation of the Chinese scholarship of past few thousand years, and the solid record of accomplishments of past Chinese scholars will inspire Chinese physicists to continue to make contributions to the world of science in the future.

In the search of for the quark-gluon plasma, it has been suggested that the production of charmonium will be suppressed in a quark-gluon plasma because of the screening of the interaction between c and $\bar{c}$ [1]. To extract information on the suppression due to the quark-gluon plasma, it is necessary to study the suppression of J/ψ production by sources different from the quark-gluon plasma. It is therefore useful to examine the mechanism of heavy quarkonium production and its propagation in nuclei [2–11].

To follow the processes of production and propagation of a charmonium or a heavy quarkonium, one needs to understand the nature of the object that is formed by the collision of partons in a hard-scattering process. This leads to the picture of a precursor formed by parton collisions that is a coherent mixture of different color, spin, and angular momentum states. The production and the subsequent interaction of this object with nucleons along its passage through a nucleus is the subject of the present study.

The present work is the result of a continuing evolution and synthesis of many previous attempts to understand production and the absorption of heavy quarkonium in a nucleus. Previous studies on heavy quarkonium production include the color evaporation model [12], the color-singlet model [13], and the color-octet model [14]. The absorption of J/ψ has been previously described as the propagation of a hybrid object $[(c\bar{c})_8 g]$ [5], the additive quark model [3], a color-singlet coherent state due to the multiple collisions with nucleons [8,9], and an incoherent admixture of color singlet and color-octet states [10,11]. The model we shall present in terms of a coherent color admixture of the precursor provides a description of the important features of the production and absorption process. There are also specific predictions of this model which can be further tested by experiment.

2. Production Process

We can study the collision of the parton b of a beam nucleon with the parton a of the target nucleon leading to the production of a Q-$\bar{Q}$ pair which later materializes directly or indirectly into a bound heavy quarkonium. The initial state Φ_{ab} of the Q-$\bar{Q}$ pair from the collision at $t_i = 0$ is represented by the state vector

$$|\Phi_{ab}(t_i) > = \mathcal{M}(ab \to Q(P/2+q)\bar{Q}(P/2-q))|Q(P/2+q)\bar{Q}(P/2-q) > \tag{1}$$

where $\mathcal{M}(ab \to Q(P/2+q)\bar{Q}(P/2-q))$ is the Feynman amplitude for the $a+b \to Q+\bar{Q}$ process, P is the center-of-mass momentum, q is the relative momentum of the Q-$\bar{Q}$ pair. For simplicity of notation, the color and azimuthal spin components are understood.

One can perform a decomposition in terms of color and angular momentum states as

$$|\Phi_{ab}(t_i) > = \sum_{CJLS} \tilde{\phi}^C_{JLS}(q)|Q\bar{Q}[^S L^C_J](P) > \tag{2}$$

where

$$\tilde{\phi}^C_{JLS}(q) = < Q\bar{Q}[^S L^C_J](P)|\mathcal{M}(ab \to Q(P/2+q)\bar{Q}(P/2-q))|Q(P/2+q)\bar{Q}(P/2-q) > \tag{3}$$

with $|Q\bar{Q}[^S L^C_J](P) >$ describing the center-of-mass motion of the $Q\bar{Q}$ pair in color state C, and angular momentum quantum numbers JLS.

The state Φ_{ab} will evolve according to perturbative QCD,

$$|\Phi_{ab}(t) > = U(t,t_i)|\Phi_{ab}(t_i) > = T \exp\{-i \int_{t_i}^t H_I dt\} |\Phi_{ab}(t_i) > \tag{4}$$

where the evolution operator $U(t,t_i)$ can be expanded out in a time-ordered perturbation series in terms of the interaction H_I. The state Φ_{ab} can be called the heavy quarkonium precursor state formed by partons a and b. Because the partons are propagators whose legs joined onto their parent nucleons, the partons are off the mass shell, with energies that depend on the invariant masses of the other products of the nucleon-nucleon collision (see [15] and Eq. (4.14) of [16]). Thus, the energy of the state Φ_{ab} also depends on the invariant masses of the other products of the nucleon-nucleon collision. It is reasonable to associate the on-shell energies of the state Φ_{ab} as an average energy of an admixture of bound states of different energies and obtain the bound state production amplitude by projecting the asymptotic precursor state at $t = \infty$ onto various bound states within a

certain energy range. For example, guided by the evaporation model, one can consider this range as between $2m_c$ and $2m_D$ for $c\bar{c}$ quarkonium production.

We describe a bound $Q\bar{Q}$ state with the quantum numbers JLS and other quantum numbers with a center-of-mass momentum P as

$$|\Psi_{JLS}; Pq> = \sqrt{\frac{2M_{JLS}}{4m_Q m_{\bar{Q}}}} \tilde{R}_{JLS}(q)|Q\bar{Q}[{}^S L_J^{(1)}](P)> . \tag{5}$$

The above state may be specified by additional quantum numbers such as the number of radial nodes, etc. For simplicity of notation, these additional quantum numbers will not be written out explicitly.

In the lowest-order perturbative QCD, the probability amplitude for the direct production of Ψ_{JLS} is obtained from projecting $\Phi_{ab}(t_i)$ onto Ψ_{JLS}. The projection is simplest in the Q-$\bar{Q}$ center-of-mass system where $P = (M_{JLS}, \mathbf{0})$ and $q = (0, \mathbf{q})$ and the probability amplitude is [17,18]

$$
\begin{aligned}
< \Psi_{JLS}; Pq|\Phi_{ab}(t=\infty)>_{\text{lowest order}} &= < \Psi_{JLS}; Pq|\Phi_{ab}(t_i)> \\
&= \sqrt{\frac{2M_{JLS}}{4m_Q m_{\bar{Q}}}} \int \frac{d^3\mathbf{q}}{(2\pi)^3} \tilde{R}_{JLS}(\mathbf{q})\tilde{\phi}_{JLS}^{(1)}(\mathbf{q}).
\end{aligned}
\tag{6}
$$

where M_{JLS} is the mass of the bound state, m_Q the mass of the quark, and we have followed the normalization of [17]. Because the bound state Ψ_{JLS} is a color-singlet state, the above projection will involve only color-singlet components of the admixture in Eq. (2).

In the next-order perturbation theory, the color-singlet bound state Ψ_{JLS} accompanied by a gluon g can be produced by the color-octet component of Φ_{ab} in Eq. (2). The probability amplitude for the production of the bound state $\Psi(JLS)$ accompanied by a gluon is

$$< [\Psi_{JLS}; Pq]g|\Phi_{ab}(t)> = < [\Psi_{JLS}; Pq]g|U(t,t_i)|\Phi_{ab}(t_i)> . \tag{7}$$

The state Ψ_{JLS} can also be produced indirectly through the production of different bound states $\Psi_{J'L'S'}$ which subsequently decay into Ψ_{JLS}. For example, in J/ψ production, a large fraction of the observed J/ψ comes from the radiative decay of χ_1 and χ_2 [19]. The production probability, including direct, indirect, and color octet contributions, is then the sum of the absolute squares of various amplitudes.

Heavy quarkonia can be produced by different parton combinations such as g-g, q-$\bar{q}$, and g-q collisions, which will lead to different precursor states. The total production probability will be the sum from all different precursor states.

For lack of a better name, we shall call the present model the coherent precursor model. Such a model has many features similar to the color evaporation model. In fact, one can interpret the phenomenological fractional coefficient in the color evaporation model as the absolute square of various projection amplitudes. The approximate success of the color evaporation model [22] also assures that this projection treatment will lead to a good description of many pieces of experimental data.

4

3. Interaction of a coherent precursor with a nucleon

The interaction of the precursor with hadron matter or other medium depends on the relative kinetic energy of this precursor with respect to the hadron matter or the medium. For processes when the precursor travels at a high energy relative to hadron matter, the interaction of the precursor with respect to a hadron in the medium can be described in terms of Pomeron and Reggeon exchanges. On the other hand, at energies where the precursor is nearly at rest with respect to the medium, the interaction depends on the binding energies of various bound states.

We shall consider here the case of charmonium production in pA collisions at a fixed target energy of a few hundred GeV [23,24], and Υ production at 800 GeV [25]. At these energies, the production of a heavy quarkonium state with $x_F > 0$ will involve the interaction of the precursor with nuclear matter at high energies. The total cross section between the precursor and a model meson $M(q_3\bar{q}_4)$ can be obtained by using the two-gluon model of the Pomeron [26–28,9]. Using the notation of [28], the elastic scattering amplitude for the exchange of two gluons between the precursor $\Phi_{ab}(Q_1\bar{Q}_2)$ and the meson $M(q_3\bar{q}_4)$ in this model is

$$\mathcal{A}(s,t) = \frac{ig^4 s}{16} \int d\mathbf{b}\, e^{-i\mathbf{Q}\cdot\mathbf{b}} < \Phi_{ab}(Q_1\bar{Q}_2)M(q_3\bar{q}_4)|V|\Phi_{ab}(Q_1\bar{Q}_2)M(q_3\bar{q}_4) > \tag{8}$$

where $s = (p(\Phi_{ab}, \text{initial}) + p(M(q_3\bar{q}_4), \text{initial}))^2$, $t = (p(\Phi_{ab}, \text{final}) - p(\Phi_{ab}, \text{initial}))^2 = Q^2$. For the exchange of two-gluons, V is [28]

$$V = \sum_a [\lambda_1^a \lambda_3^a V_{13} + (\lambda_2^a)^T (\lambda_4^a)^T V_{24} - \lambda_1^a (\lambda_4^a)^T V_{14} - (\lambda_2^a)^T \lambda_3^a V_{13}]^2, \tag{9}$$

where λ_i^a is the generator of SU(3) associated with the ith quark, V_{ij} is the interaction between the i and the jth quark or antiquark. Because $(q_3\bar{q}_4)$ is coupled to a color-singlet state, the matrix element in the above equation between different color states vanishes, and we have

$$\mathcal{A}(s,t) \tag{10}$$

$$= \sum_{CJLS} \frac{ig^4 s}{16} \int d\mathbf{b}\, dr_{12} dr_{34} e^{-i\mathbf{Q}\cdot\mathbf{b}} |\phi_{JLS}^C(\mathbf{r}_{12})|^2 |R(\mathbf{r}_{34})|^2 <(Q_1\bar{Q}_2)^C(q_3\bar{q}_4)^1|V|(Q_1\bar{Q}_2)^C(q_3\bar{q}_4)^1>,$$

where $R(\mathbf{r}_{34})$ is the q_3-$\bar{q}_4$ relative wave function in the model meson $M(q_3\bar{q}_4)$. One can use the optical theorem to obtain the total cross section for this coherent precursor. One can compare the total cross section $\sigma_{JLS}^C(ab)$ obtained from the forward elastic scattering amplitude for the case if Φ_{ab} is a (properly normalized) pure state of $\phi_{JLS}^C(\mathbf{r}_{12})|(Q_1\bar{Q}_2[^S L_J^C](P) >$. Then Eq. (10) gives the total cross section between the precursor (formed by the partons a and b) given by

$$\sigma_{tot}(ab) = \sum_{CJLS} f_{JLS}^C(ab)\, \sigma_{JLS}^C(ab) \tag{11}$$

where $\quad f_{JLS}^C(ab) = \int d\mathbf{r}_{12} |\phi_{JLS}^C(\mathbf{r}_{12})|^2 / < \Phi_{ab}|\Phi_{ab} > .$ $\tag{12}$

The above describes the cross section for a coherent precursor colliding with a meson. The result of Eq. (12) can also be generalized to that for the collision between the precursor and a nucleon as is done in [28].

From the work of Dolejší and Hüfner [28], and Wong [9], we know that the $(Q\bar{Q})^{(1)}$-nucleon total cross section for a pure color-singlet $(Q\bar{Q})^{(1)}$ state is approximately proportional to the root-mean-square of the separation between Q and $\bar{Q}$. The coherent precursor produced after the hard-scattering process has a small spatial extension, so it is reasonable to take the color-singlet cross sections $\sigma_{tot}^{(1)}$ for different JLS states to be small and nearly equal. The $(Q\bar{Q})^{(8)}$-nucleon total cross section for a pure color-octet $(Q\bar{Q})^{(8)}$ state is insensitive to the Q-$\bar{Q}$ separation. This approximate independence of the color-octet cross section with respect to the Q-$\bar{Q}$ separation [28,3] allows us to approximate the color-octet cross sections for different color-octet JLS states by a single $\sigma_{tot}^{(8)}$. Therefore, the precursor-nucleon total cross section is

$$\sigma_{tot}(ab) \approx f^{(1)}(ab)\,\sigma_{tot}^{(1)} + f^{(8)}(ab)\,\sigma_{tot}^{(8)}, \tag{13}$$

$$\text{where} \quad f^C(ab) = \sum_{JLS} f_{JLS}^C(ab). \tag{14}$$

In heavy quarkonium production, there can be different combinations of partons leading to different precursor states, and each precursor has a total precursor-nucleon cross section given by an expression such as Eq. (13). Thus, the precursor cross section depends on the color-octet fraction of the precursor.

The most important parton collisions for heavy quarkonium production are the gg and $q\bar{q}$ collisions. In gg collisions, the coherent precursor can be in color-singlet and color-octet states, while in $q\bar{q}$ collisions, the precursor is a color-octet state in the lowest order. For the total yield at fixed target energies, the dominant production process comes from the collision of gluons [22].

In the kinematic region where the collision of the precursor with nucleons takes place at high energies, as in the production of heavy quarkonium in the region of $x_F > 0$ in pA collisions, the binding energy of the heavy quarkonium is much smaller than the precursor-nucleon collision energy. The probability for the breakup of the Q-$\bar{Q}$ pair into $Q\bar{q}$ and $q\bar{Q}$ by combining with light quarks is large in a precursor-nucleon collision. It is reasonable to assume that in high-energy precursor-nucleon collisions the absorption (i.e. breakup) cross section, $\sigma_{abs}(ab)$, is approximately given by the precursor-nucleon total cross section $\sigma_{tot}(ab)$ of Eq. (13).

4. Propagation of a coherent precursor in nuclear matter

We consider a pA collision in which a heavy quarkonium precursor is produced in one of the nucleon-nucleon collisions and the precursor subsequently travels in the nuclear medium of the target nucleus. Because of the coherence of the precursor, it propagates through the nuclear medium as a single object with a single absorption cross section after its production. When the precursor travels inside the nuclear medium, the time of evolution t can be represented equivalently by the corresponding path length L/v, where v is the velocity of the precursor in the medium. The state vector after propagating a distance L in the nuclear medium is related to the state vector after production by

$$|\Phi_{ab}(L)> = e^{-\rho\sigma_{abs}(ab)L/2}|\Phi_{ab}(L=0)>, \tag{15}$$

where $\sigma_{abs}(ab) \equiv \sigma_{abs}(\Phi_{ab}-N)$ is the precursor absorption cross section for the collision of the precursor Φ_{ab} with a nucleon, and ρ is the nuclear matter number density.

After the passage through a path length of L in the nuclear matter, the amplitude for the production of a bound state Ψ_{JLS} is obtained by projecting the state vector $\Phi_{ab}(L)$ onto the bound state Ψ_{JLS}. Therefore,

$$< \Psi_{JLS}; Pq|\Phi_{ab}(L) >= e^{-\rho\sigma_{abs}(ab)L/2} < \Psi_{JLS}; Pq|\Phi_{ab}(L=0) > \tag{16}$$

and for the octet production of $|\Psi_{JLS}; Pq >$ with the emission of a gluon

$$< [\Psi_{JLS}; Pq]g|U(t,L/v)|\Phi_{ab}(L) >= e^{-\rho\sigma_{abs}(ab)L/2} < [\Psi_{JLS}; Pq]g|U(t,0)|\Phi_{ab}(L=0) > . \tag{17}$$

When we include precursors from different parton collisions leading to the production of the bound state Ψ_{JLS}, there will be different survival factors $e^{-\rho\sigma_{abs}(ab)L/2}$ for different parton combinations a-b. At fixed-target energies, where the total yield of J/ψ in the forward direction is dominated by contributions from gg collisions [22], one expects that there is essentially only a single survival factor for the total yield in forward directions.

5. Consequences of the coherent precursor model

One can outline a few distinct consequences of the model we have presented. In the situation when only a single absorption combination of partons dominates the production process, the ratio of the production of various bound states in a pA collision will be independent of the mass number of the nucleus. This arises because the precursor is absorbed in its passage through nuclear matter by a single precursor-nucleon cross section $\sigma_{abs}(ab)$, and the production of all different bound states comes from the projection of the precursor state onto the bound states after the absorption. For example, as a consequence of Eqs. (16),

$$\frac{|< \psi'|\Phi_{gg}(L) > |^2}{|< \psi|\Phi_{gg}(L) > |^2} = \frac{|< \psi'|\Phi_{gg}(L=0) > |^2}{|< \psi|\Phi_{gg}(L=0) > |^2} . \tag{18}$$

There is a similar relation for the production amplitude from the color-octet amplitudes because of Eq. (17). Therefore, we have

$$\frac{\sigma(\psi')(L)}{\sigma(\psi)(L)} = \frac{\sigma(\psi')(L=0)}{\sigma(\psi)(L=0)} \quad \text{or} \quad \frac{\sigma(pA \to \psi' X)}{\sigma(pA \to \psi X)} = \frac{\sigma(pp \to \psi' X)}{\sigma(pp \to \psi X)}, \tag{19}$$

which is independent of A. A similar independence with A is predicted for Υ'/Υ. Experimentally, the ratio $\psi'/(J/\psi)$ is observed to be approximately a constant of the atomic numbers [24], in agreement with the present picture. The experimental yields of Υ and Υ' have considerable uncertainties, but within the large experimental uncertainties the ratio $\sigma(pA \to \Upsilon' X)/\sigma(pA \to \Upsilon X)$ is approximately independent of A [25]. The present model predicts further that the ratio of the χ yield to the J/ψ yield will also be independent of the mass number in pA collisions. It will be of interest to test such a prediction in the future.

A similar model of coherent state production was put forth earlier by Dolejší and Hüfner [28], and Wong [9], with some major differences. In these models, a color-singlet coherent

state of J/ψ and ψ' is assumed to come from the successive multiple scattering of the precursor with a row of nucleons, whereas in the present model, a coherent state of both color, angular momentum, and other quantum numbers is formed in the hard-scattering process before multiple collisions with nucleons and collisions with nucleons at high energy are assumed to lead to absorption, and not to the change of the coherent mixture.

We note that the total cross section σ_{tot} for a coherent color admixture is the weighted sum of the corresponding cross sections for pure color-singlet and color-octet states. For a coherent state that is formed after the hard scattering, the spatial extension of the state is small. One expects that $\sigma_{tot}^{(1)}$ should be nearly zero while $\sigma_{tot}^{(8)}$, which is nearly independent of the radial size of the state, is very large, of the order of 30 to 60 mb. Thus, an absorption cross section of the order of 6 mb extracted from the experimental survival factor in pA data [2,4,6] for J/ψ and ψ' can be understood as arising from a color-octet fraction $f^{(8)}$ of the order of 10% to 20%, as given by Eq. (13).

Experimentally, the production cross sections for χ_1, χ_2, and direct J/ψ are 131 nb, 188 nb, and 102 nb, respectively, for π-N collisions at 300 GeV [19]. Therefore, direct J/ψ production is about 25% of the total yield of charmonium. As χ_1 and χ_2 are produced predominantly via the color-singlet states, while the direct J/ψ production comes predominantly from color-octet states [20,21], it is therefore encouraging that the fraction of 25% of direct J/ψ among the total charmonium yield is of the same order as the color-octet fraction $f^{(8)}$ of about 10%-20% that is consistent with the absorption cross section and the theoretical estimates from the two-gluon model of the Pomeron. It will be of interest to calculate this color-octet fraction $f^{(8)}$ from Eqs. (12) and (14) theoretically. This may rectify a previously unsatisfactory outcome when the precursor is described as a mixed state with an incoherent color admixture. The incoherent color admixture description of the precursor is not satisfactory because the absorption cross section for the color-octet state is found, in this picture, to be about 15 to 20 mb in [10] and 11 mb in [11], too small to be consistent with the theoretical estimates of about 30-60 mb from the two-gluon model of the Pomeron [28,9].

Finally, in different kinematic regions, the importance of the different parton production components will change [22]. For example, while gg fusion dominates in the region of small x_F, which gives the largest yield, the yield at $x_F \gg 0.6$ is dominated by q-$\bar{q}$ collisions. Unlike the gg fusion which can lead to both color-singlet and color-octet components, $q\bar{q}$ collisions lead to color-octet in the lowest-order approximation. The present model will predict an increase in the absorption cross section in the region of large x_F due to the large color-octet precursor-nucleon cross section. Experimental data at different x_F show an increase in the effective absorption cross section as x_F increases [10,23,24]. However, the effect of energy loss needs to be taken into account at these kinematic regions to confirm the effect that the color-octet state leads to a very large increase in the absorption of the precursor at $x_F > 0.6$.

In the transition region when two different precursors contribute about equally, as in the region around $x_f \sim 0.6$, the survival probability is determined by two different exponential survival factors, with two different absorption cross sections for the two kinds of precursors, as a function of the nuclear matter path length. Future experimental investigations on the change of the characteristics of the mass dependence from small x_f to large x_f will be of interest.

8

In conclusion, the coherent precursor model provides a reasonable description of the production and propagation of the object form before the formation of the bound states. Further tests of the model can be carried out to confront with experiment.

The author would like to thank Dr. C. W. Wong for comments and communications. He also wishes to thank Drs. R. Blankenbecler, H. W. Crater, J. C. Peng, and J. S. Wu for valuable discussions.

REFERENCES

1. T. Matsui and H. Satz, Phys. Lett. B178, 416 (1986).
2. C. Gerschel and J. Hüfner, Phys. Lett. B207, 253 (1988); C. Gerschel and J. Hüfner, Nucl. Phys. A544, 513c (1992).
3. C. Y. Wong, Phy. Rev. Lett. 76, 196 (1996).
4. C. Y. Wong, Nucl. Phys. A610, 434c (1996);, C. Y. Wong, Phys. Rev. C55, 2621 (1997); C. Y. Wong, to be published in Nuclear Physics A (hep-ph/9706504).
5. D. Kharzeev and H. Satz, Phys. Lett. B **366**, 316 (1996).
6. D. Kharzeev, C. Lourenço, M. Nardi, and H. Satz, hep-ph/9612217.
7. S. Gavin and R. Vogt, Nucl. Phys. B345, 104 (1990); S. Gavin and R. Vogt, Nucl. Phys. A610, 442c (1996).
8. J. Hüfner and B. Kopeliovich, Phys. Rev. Lett. 76, 192 (1996).
9. C. W. Wong, Phys. Rev. D54, R4199 (1996).
10. C. Y. Wong and C. W. Wong, hep-ph/9604282.
11. C. F. Qiao, X. F. Zhang, W. Q. Chao, hep-ph/9708258.
12. H. Fritzsch, Phys. Lett. B67, 217 (1977).
13. Chang Chao-Hsi, Nucl. Phys. B172, 425 (1980); E. L. Berger and D. Jones, Phys. Rev. D23, 1521 (1981); R. Baier and R. Rückl, Zeit. Phys. C19, 251 (1983).
14. G. T. Bodwin, E. Braaten, and G. P. Lepage, Phys. Rev. D51, 1125 (1995).
15. E. A. Schmidt, and R. Blankenbecler, Phys. rev. D15, 332 (1977)
16. C. Y. Wong, *Introduction to High-Energy Heavy-Ion Collisions*, World Scientific Publishing Company, 1994.
17. M. E. Peskin and D. V. Schroeder, *An Introduction to Quantum Field Theory*, Addision Wesley Publishing Company, 1995.
18. H. W. Crater, Phys. Rev. A44, 7065 (1991).
19. L. Antoniazzi *et al.*, E705 Collaboration, Phys. Rev. Lett. 70, 383 (1993).
20. M. Beneke, I. Z. Rothstein, Phys.Rev. D 54, 2005 (1996).
21. Wai-Keung Tang and M. Vänttinen, Phys. Rev. D 53, 4851 (1996).
22. M. S. Kowitt *et al.*, Phys. Rev. Lett. 72, 1318 (1994); J. C. Peng, D. M. Jensen, Y. C. Chen, Phys. Lett. B344, 1 (1995).
23. J. Badier *et al.*, NA3 Collaboration, Z. Phys. C **20**, 101 (1983); C. Lourenço, NA38/NA50 Collaboration, Nucl. Phys. A610, 552c (1996).
24. D. M. Alde *et al.*, Phys. Rev. Lett. 66, 133 (1991).
25. D. M. Alde *et al.*, Phys. Rev. Lett. 66, 2285 (1991).
26. F. E. Low, Phys. Rev. D12, 163 (1975).
27. S. Nussinov, Phys. Rev. Lett. 34, 1286 (1975).
28. J. Dolejší and J. Hüfner, Z. Phys. C54, 489 (1992).