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Charmonium cross-sections and the QGP

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Abstract. In this contribution we summarize experimental information and theoretical results for the dissociation cross-sections of charmonium by light hadrons, which are of great importance for the identification of a quark-gluon plasma (QGP). Recent theoretical predictions for these cross-sections differ by orders of magnitude over the physically relevant energy range. The methods discussed here include a color-dipole model, meson exchange models, a quark interchange model, and QCD sum rules.

PACS. 25.75.-q Relativistic heavy-ion collisions – 25.75.Dw Particle and resonance production

1 Introduction

A rather exotic process in hadron-hadron scattering, the dissociation of charmonia through collisions with light hadrons, has recently been identified as of great importance to the RHIC community. This interest has arisen from the suggestion by Matsui and Satz [1] that suppression of J/ψ production could be used as a signature for the formation of a quark-gluon plasma.

The suggested mechanism for QGP-suppression of charmonium is that a QGP will screen the linear confining interaction between quarks, so that a $c\bar{c}$-pair produced within a QGP is unlikely to form a bound $c\bar{c}$ charmonium resonance as in fig. 1, but will instead separate into open-charm mesons.

Even if this simple picture of $c\bar{c}$ production in a QGP is qualitatively correct, interpretation of this signature requires an understanding of the competing effects of direct charm production and scattering by the initial relativistic nucleons [2], as well as the effect of subsequent dissociation of charmonia through collisions with the many "co-moving" light hadrons produced in a heavy-ion collision. It is thus of great importance for QGP searches using the charmonium-suppression signature to establish the approximate scale of these low-energy $c\bar{c}$ + light-hadron co-mover dissociation cross-sections.

To summarize, if charmonium + light-hadron dissociation cross-sections are small (case 1, top of fig. 1) and the background of direct charm production from the initial nucleons is understood, one may have a useful signature for QGP formation. Conversely, if the co-mover dissociation cross-sections are large (case 2, bottom of fig. 1), one must distinguish between QGP-reduced charmonium production and subsequent dissociative scattering, and the interpretation of the J/ψ signal will be biased unless these dissociation cross-sections are included in the event simulations.

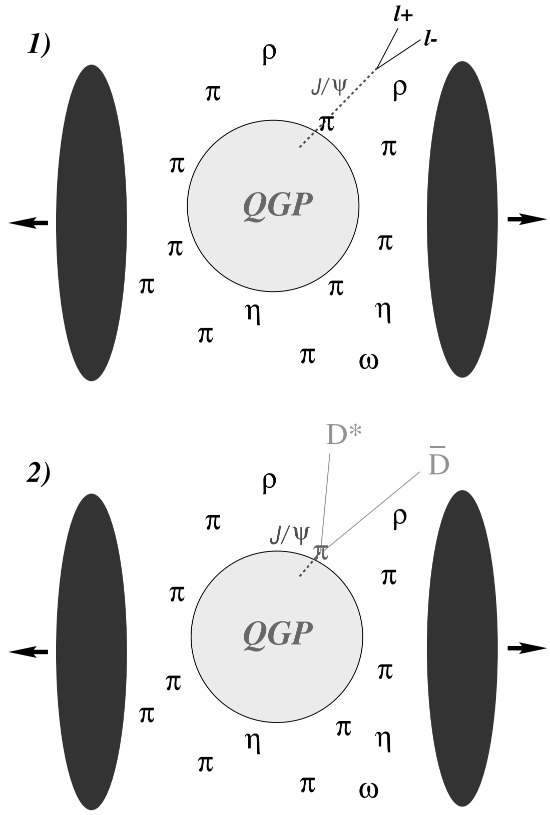

Fig. 1. Matsui and Satz speculated that J/ψ production would be strongly suppressed if a QGP has been formed. We address the subsequent effect of J/ψ absorption by light co-movers, which may be 1) weak, or 2) strong.

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2 Experiment

Unfortunately we have no charmonium beams or targets, so experimental low-energy charmonium cross-sections must be inferred indirectly and are poorly known. The earliest estimates of charmonium cross-sections at moderate energies came from J/ψ photoproduction experiments in the mid 1970s, which were interpreted in terms of a $J/\psi + N$ total cross-section. Early Fermilab and SLAC photoproduction experiments gave rough estimates of $\sim 1\,\mathrm{mb}$ for $\sigma_{J/\psi+N}$, assuming vector dominance, for photon energies from $E_\gamma \approx 13$ to $200\,\mathrm{GeV}$ [3,4]. A subsequent SLAC photoproduction experiment in 1977 used the A-dependence of J/ψ absorption to infer a rather larger cross-section of $\sigma_{J/\psi+N} = 3.5 \pm 0.8\,\mathrm{mb}$ at $E_\gamma \approx 17\,\mathrm{GeV}$ ($\sqrt{s} \approx 6\,\mathrm{GeV}$) [5]. The vector dominance hypothesis may have led to an underestimate of the cross-section in the earlier references [6].

In heavy-ion collisions these cross-sections may be estimated from the ratio of lepton pairs produced in the J/ψ peak to "background" Drell-Yan pairs nearby in energy. Since the J/ψ must reach the exterior of the nuclear target to decay into a sharp mass peak, this ratio gives us an estimate of the absorption cross-section through the classical survival probability formula,

$$\sigma\big(J/\psi \longrightarrow \mu^+\mu^-\big)/\sigma\big(\text{Drell-Yan } \mu^+\mu^-\big) = \exp\big(-\rho\sigma^{abs}_{J/\psi+N}L\big), \qquad (1)$$

where ρ is the mean nucleon density and L is the estimated mean path length in the experimental nuclear system. A "naive" interpretation of the J/ψ production data from collisions of various nuclear species using this formula gives $\sigma^{abs}_{J/\psi+N} \approx 6\,\mathrm{mb}$ at $\sqrt{s} \approx 10\,\mathrm{GeV}$ [7], with a numerically similar result for the ψ' (see fig. 2).

Of course one may raise many questions about the validity of this simple estimate, such as the importance of shadowing in Drell-Yan, the neglect of J/ψ scattering by other light hadrons formed in the collision (such as π and ρ), and the assumption of a single, constant $J/\psi+N$ cross-section in all circumstances.

Recently, concerns have been expressed that the J/ψ and ψ' wave functions have not had sufficient time to form within the nucleus in these collisions, so experiment may instead be measuring the cross-section for a small initial $c\bar{c}$ "premeson" on a nucleon. One can increase the time spent in the interior of the nuclear system by selecting small and even negative x_{F} events, as has been done by E866 at Fermilab. As discussed by He, Hüfner and Kopeliovich [8], this leads one to infer $\sigma^{abs}_{J/\psi+N} = 2.8 \pm 0.3\,\mathrm{mb}$ and $\sigma^{abs}_{\psi'+N} = 10.5 \pm 3.6\,\mathrm{mb}$ respectively, also at $\sqrt{s} \approx 10\,\mathrm{GeV}$. This is rather more satisfying to people who have an intuitive notion that the larger ψ' should have a larger reaction cross-section. Actually the connection between cross-section and physical extent is less direct (compare KN and $\bar{K}N$), and in any case the relative proximity of inelastic thresholds alone would suggest a larger ψ' cross-section. These experiments also suggest a preference for dissociation over elastic cross-sections at $\sqrt{s} \approx 10\,\mathrm{GeV}$ by roughly a factor of 30 [8].

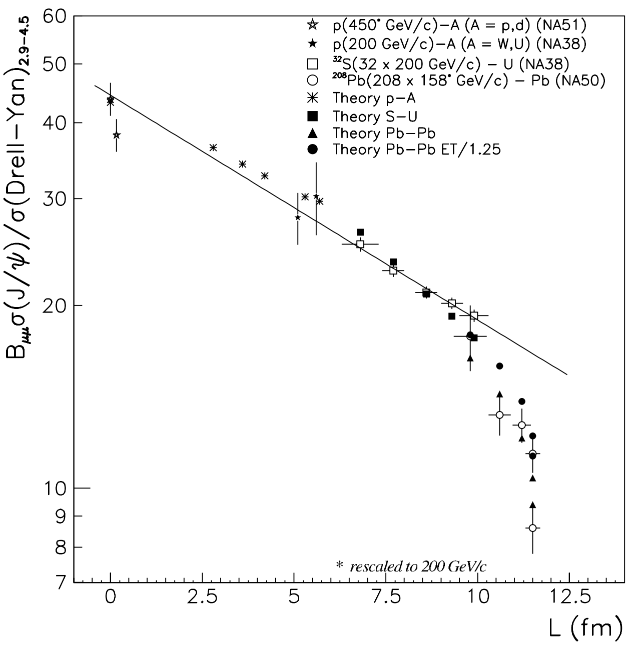

Fig. 2. A fit of eq. (1) to experimental J/ψ production *versus* path length [7]; the line corresponds to 6.2 mb.

3 Theory: introduction

To quote B. Müller, "...the state of the theory of interactions between J/ψ and light hadrons is embarrassing ... Only three serious calculations exist (after more than 10 years of intense discussions about this issue!) and their results differ by at least two orders of magnitude in the relevant energy range.... There is a lot to do for those who would like to make a serious contribution to an important topic." (*Quark Matter 99* Summary, ref. [9]).

The theoretical situation has improved considerably since these remarks. A partial list of recent $c\bar{c}$ + light-hadron cross-section calculations is given in table 1.

Table 1. A representative set of $c\bar{c}$ + light-hadron cross-section calculations.

Method	Init State	Reference
color-dipole	$J/\psi + N$	[10]
	$J/\psi + N$; $\psi' + N$; $\chi + N$	[11]
meson ex.	$J/\psi + \pi$	[12]
	$J/\psi + \pi, \rho$	[13]
	$J/\psi + \pi, \rho$	[14]
	$J/\psi + N$	[15,16]
	$J/\psi + \pi, K, \rho, N$	[17,18]
quark int.	$J/\psi + \pi$	[12,19]
	$J/\psi + \pi, \rho$; $\psi' + \pi, \rho$	[20]
	$(J/\psi, \psi', \chi) + (\pi, \rho, K)$	[21]
	$J/\psi + \pi, N$; $\psi' + \pi, N$	[22]
QCD sum rules	$J/\psi + \pi$	[23]

Approaches to calculating cross-sections of charmonia on light hadrons have to date usually employed one of three descriptions, which are a high-energy diffractive model originally due to Bhanot and Peskin [24], t-channel meson exchange as first discussed by Matinyan and Müller [13], and the quark interchange model discussed here. Unfortunately the space available does not allow a detailed discussion of the two earlier approaches; here we simply tabulate references that have used the various methods (table 1), and note that there are serious problems with all of these approaches (see, for example, the discussion in ref. [25]).

4 Theory: quark interchange

One may also calculate these cross-sections in the quark model, using nonrelativistic quark model wave functions and the quark interchange scattering mechanism, driven by the Born-order matrix element of the standard quark model Hamiltonian. This technique, which has no free parameters once quark model wave functions and the interquark Hamiltonian are specified, has been shown to compare reasonably well with experimental low-energy hadron scattering data near threshold for a wide range of no-annihilation reactions [26,27]. In meson-meson scattering there are four distinct diagrams (see fig. 3), each of which has an associated overlap integral of quark model meson wave functions convolved with the interquark Hamiltonian. Constituent interchange is forced at Born-order because $H_I \propto \lambda^a \cdot \lambda^a$ changes each initial color-singlet $q\bar{q}$ meson into a color-octet; these have a nonzero projection onto color-singlet final-state mesons after quark line interchange. The Feynman rules for these diagrams were given by Barnes and Swanson [26].

The first charmonium cross-section calculation using this approach was due to Martins, Blaschke and Quack [19], who considered the reactions $J/\psi + \pi \to D^*\bar{D}$+h.c. and $D^*\bar{D}^*$. (The amplitude for $J/\psi+\pi \to D\bar{D}$ is zero in the nonrelativistic quark model without spin-orbit forces, and has been found to be quite weak in a relativized calculation [12].) Martins *et al.* found that these exclusive final states have numerically rather similar cross-sections (except for their different thresholds), and gave a maximum total cross-section of about 7 mb at $\sqrt{s} \approx 4.1$ GeV. A quark interchange calculation of $J/\psi+N$ and $\psi' + N$ cross-sections using a simplified quark + diquark model of the nucleon [22] also found several-mb peak cross-sections not far above threshold.

Our collaboration recently carried out similar quark interchange model calculations (Wong *et al.* [20,21]). We used numerically determined Coulomb plus linear plus hyperfine quark potential model wave functions, and evaluated the Born-order meson-meson T-matrix represented by the diagrams of fig. 6. The parameters used for the examples shown here are $\alpha_s = 0.6$, b (string tension) $= 0.18\,\mathrm{GeV}^2$, $m_{u,d} = 0.33\,\mathrm{GeV}$, $m_c = 1.6\,\mathrm{GeV}$, and the OGE contact hyperfine smearing parameter was $\sigma = 0.8\,\mathrm{GeV}$; these are all reasonably well-established nonrelativistic quark model parameters. We generated wave functions

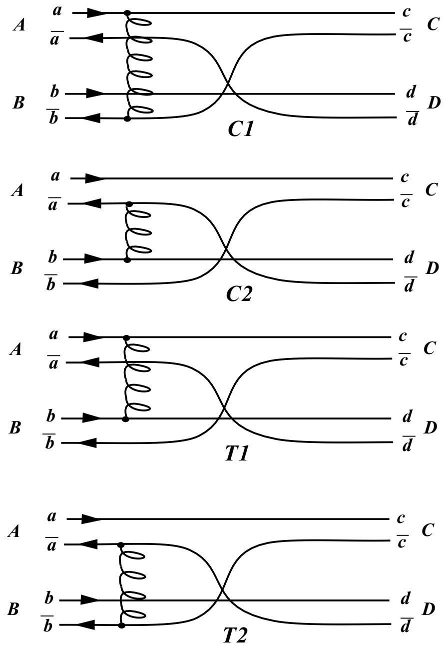

Fig. 3. The four quark interchange scattering diagrams evaluated in the $J/\psi + q\bar{q}$ cross-section calculation [19,20,22]. The "exchange" is the full quark model interaction Hamiltonian H_I.

for each meson by solving the radial Schrödinger equation with this interaction, and evaluated the scattering overlap integrals represented by each diagram in fig. 6 for each of the three interactions, using Monte Carlo methods. The full hadron scattering amplitudes were then evaluated in the CM frame given these overlap integrals by attaching color, flavor and spin matrix elements, and were projected onto L-moments to separate the different partial waves (here including $L = 0$ to $L = 4$). In converting the amplitude moments to physical cross-sections we assumed physical hadron masses, relativistic dispersion relations and relativistic phase space. Recovery of the known analytic results for scattering amplitudes and cross-sections given SHO wave functions and this quark model interaction provided a check of the programs.

There is a formal ambiguity as to whether we allow the interaction before quark interchange, as in fig. 6 (prior), or after (post). This "post-prior ambiguity" is well known from studies of exchange collisions in atomic physics, and one may show that the final scattering amplitudes are identical in a nonrelativistic Schrödinger formalism. Since we have relativistic particles, we do find a significant post-prior discrepancy in some cases, as discussed in ref. [20]. The numerical results shown here use the "prior" formalism.

In fig. 4 we show our results for the $J/\psi + \pi^+ \to \bar{D}^\circ D^{*+}$ and $\psi'+\pi^+ \to \bar{D}^\circ D^{*+}$ dissociation cross-sections. We find a somewhat smaller $J/\psi + \pi$ cross-section than Blaschke *et al.*; after summing over $\bar{D}D^*$, $\bar{D}^*D$ and $\bar{D}^*D^*$ final channels, our final result [20] has a maximum of only about 1 mb at $\sqrt{s} \approx 4.0$ GeV. The important difference between our work and Blaschke *et al.* is in the treatment

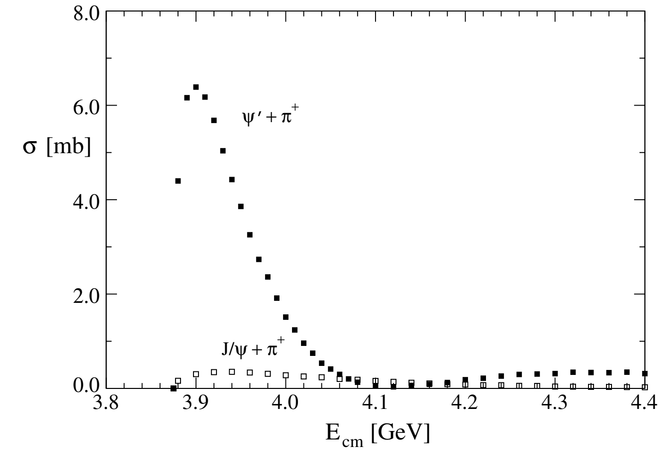

Fig. 4. Constituent interchange model predictions for the cross-sections $J/\psi + \pi^+ \to \bar{D}^\circ D^{*+}$ and $\psi' + \pi \to \bar{D}^\circ D^{*+}$.

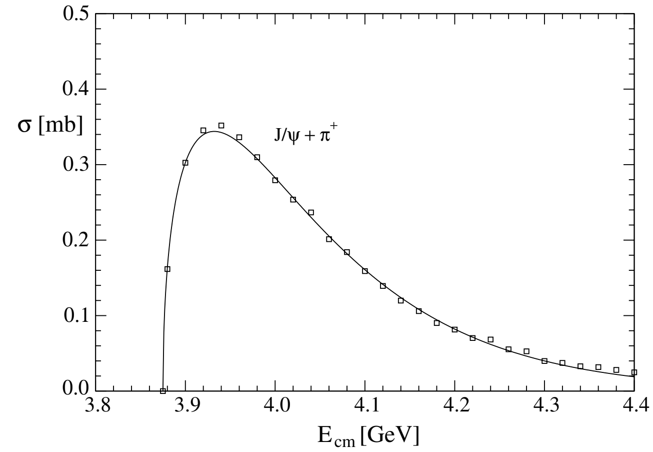

Fig. 6. A fit of eq. (2) to our numerical cross-section for the reaction $J/\psi + \pi^+ \to \bar{D}^\circ D^{*+}$.

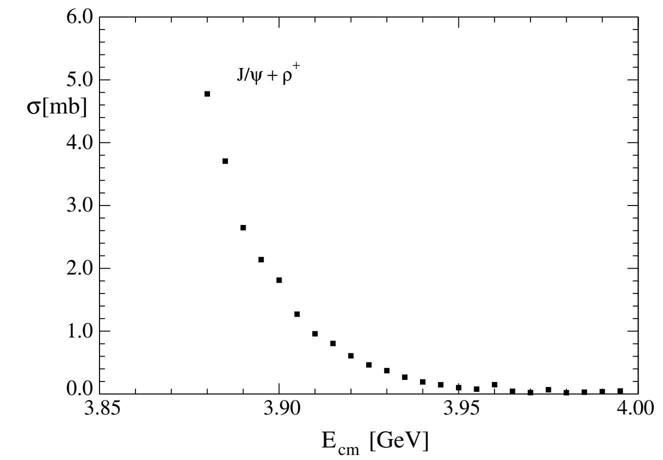

Fig. 5. Constituent interchange model prediction for exothermic reaction $J/\psi + \rho^+ \to \bar{D}^o D^+$. Some scatter of numerical results due to the Monte Carlo evaluation of overlap integrals is evident.

of the confining interaction; for simplicity, Blaschke *et al.* treated confinement as a color-independent Gaussian potential that acts only between quark and antiquark (hence they include only diagrams $C1$ and $C2$), whereas we assumed the standard $\lambda^a \cdot \lambda^a$ linear confining potential between all pairs of constituents. We find destructive interference between the C and T diagrams, leading to a much reduced $J/\psi + \pi$ peak cross-section relative to Blaschke *et al.*

Evaluation of the $\psi' + \pi^+$ cross-section involves a simple change to a $2S$ $c\bar{c}$ wave function and a change of phase space; this gave a rather large (ca. 12 mb) cross-section maximum (twice fig. 7 when we add $\bar{D}D^*$ and $\bar{D}^*D$), due mainly to the proximity of the initial $\psi' + \pi$ mass to the open-charm DD^* threshold. Our $c\bar{c} + q\bar{q}$ cross-sections typically have their strongest support just a few hundred MeV in $\sqrt{s}$ above threshold, since the overlap integrals are damped by the tails of the wave functions at higher energies.

The predicted $J/\psi + \rho$ cross-section is shown in fig. 5; this is very large near threshold for the simple reason that it is exothermic; there is a $1/v_i$ divergence in this cross-section (and those of most higher-mass initial mesons) as we approach threshold.

Although our scattering amplitudes and cross-sections are evaluated numerically and have no simple functional form given realistic quark model wave functions, it is nonetheless interesting that a simple function gives a useful parametrization of our cross-sections at low energies. This function is

$$\sigma(s) = \sigma_{\max}(\epsilon/\epsilon_{\max})^p e^{p(1-\epsilon/\epsilon_{\max})}, \tag{2}$$

where $\epsilon = \sqrt{s} - M_C - M_D$ and $\sigma_{\max}$ is the maximum value of the cross-section, at $\epsilon_{\max}$. As an example, in fig. 6 we show our numerical results for the reaction $J/\psi + \pi^+ \to \bar{D}^o D^{*+}$ and a fit using the function in eq. (2). The fitted parameters are $\sigma_{\max} = 0.344\,\text{mb}$, $\epsilon_{\max} = 57.1\,\text{MeV}$ and $p = 0.485$. Note that the fitted power is quite close to the $p = 1/2$ expected for an S-wave final state; the threshold exponent p is determined specified by the angular quantum numbers of the hadrons, and is $\pm 1/2 + L^{\text{CD}}_{\min}$ (for endothermic/exothermic), where $L^{\text{CD}}_{\min}$ is the lowest angular momentum allowed for the final meson pair CD. Our moment projection confirms that this cross-section is dominantly S-wave at low energies.

5 Theory: QCD sum rules

Finally, a very recent and exciting development is the application of QCD rum rules to the determination of low-energy charmonium cross-sections. This work has been carried out by Navarra *et al.* [23], who consider the processes $J/\psi + \pi \to DD, DD^*$ and D^*D^*. They find a ca. 1 mb dissociation cross-section to these final states at $\sqrt{s} \approx 4.1\,\text{GeV}$ (see fig. 7), similar in scale to the meson exchange and quark interchange results at this energy. Note however that the QCD sum rule calculation with current approximations predicts cross-sections that continue to rise with increasing $\sqrt{s}$.

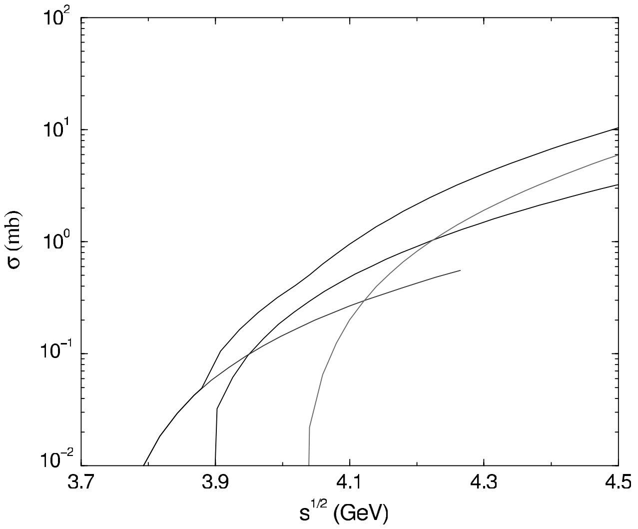

Fig. 7. QCD sum rule results for $J/\psi + \pi$ dissociation cross-sections [23]. With increasing $\sqrt{s}$ along the x-axis one encounters the cross-sections for $J/\psi + \pi \to DD$; DD^*; and D^*D^*. The total cross-section (the sum of these three) is also shown.

6 Conclusions

We have reviewed the experimental status and recent theoretical predictions for the cross-sections of $c\bar{c}$-mesons on light hadrons, which is a topic of great interest for the interpretation of heavy-ion collisions. Three scattering models are currently being investigated, which are color-dipole, t-channel meson exchange, and quark interchange. Theoretical cross-sections have also been estimated using QCD sum rules. The color-dipole approach gives very small cross-sections at low energies, whereas the other approaches typically find cross-sections of ~ 1 mb for endothermic reactions within several hundred MeV of threshold. Most exothermic charm dissociation cross-sections (for example $J/\psi + \rho \to DD$) diverge as we approach threshold. The models predict very different energy dependences for these cross-sections at higher energies.

Should it be possible to determine these low-energy cross-sections experimentally, especially to exclusive final states, comparison with these theoretical results should lead to a much improved understanding of the mechanisms of low-energy hadron-hadron scattering.

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