Proton-proton spin correlations at charm threshold and quarkonium bound to nuclei

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The anomalous behavior of the spin-spin correlation at large momentum transfer in pp elastic scattering is described in terms of the degrees of freedom associated with the onset of the charm threshold. A nonperturbative analysis based on the symmetries of QCD is used to extract the relevant dynamics of the charmonium-proton interaction. The enhancement to pp amplitudes and their phase follow from analyticity and unitarity, giving a plausible explanation of the spin anomaly. The interaction between $c\bar{c}$ and light quarks in nuclei may form a distinct kind of nuclear matter: nuclear bound quarkonium. [S0556-2821(98)02315-7]

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The fundamental description of the strong forces in terms of structureless constituents which carry the symmetries within the hadrons, and their interaction in terms of gluonic fields, is the basis of quantum chromodynamics (QCD). Despite considerable success in the application of QCD in the perturbative regime (PQCD) [1], there are important discrepancies with measurements related to the production and decay of heavy quark systems [2] and the study of spin effects at high energy [3]. A notorious example is the unexpected result observed in the polarization correlation A_{NN} found in proton-proton collisions at large energy and momentum transfer [4]. At $\sqrt{s}$ near 5 GeV and $\theta_{\mathrm{c.m.}}=90°$ the rate of protons scattering with incident spins parallel and normal to the scattering plane, relative to the protons scattering with antiparallel spins, rises dramatically with A_{NN} reaching a value of 60% in a region where scaling behavior is expected.

A simple explanation for this anomaly has its origin in the observation that at $\sqrt{s}=5$ GeV new degrees of freedom associated with the onset of a heavy-quark–antiquark threshold could invalidate the scale-invariant nature of the basic constituent interaction at high energies by the interaction of light and heavy quarks at low relative velocity [5]. Other models have also been advanced to explain the spin anomaly, but they imply a radical departure from the PQCD framework or the standard model [6], introducing extraneous dynamical effects. The phenomenological analysis of Ref. [5], based on $J=L=S=1$ broad resonance structures at the strange and charm thresholds interfering with PQCD quark-interchange amplitudes, successfully describes the anomalous p_{lab} dependence of the spin correlation but lacks of a clear dynamical content since the parameters of the model are chosen to fit the data.

It is one of the main objectives of the present paper to show that the enhancement of the proton-proton elastic amplitudes close to the charm threshold is obtained from precise knowledge of the dynamics of heavy quarkonium with light hadrons. The spin correlation close to the threshold is determined from unitarity and analyticity without introducing arbitrary parameters and is largely predictable from basic principles.

The study of the interaction of quarkonia with light hadrons is of particular relevance to a better understanding of the dynamics of gluons from a new perspective. Since different quark flavors are involved in the quarkonium-nucleon interaction, there is no quark exchange to first order in elastic scattering [7] and multiple gluon exchange is the dominant contribution [8]. Remarkably, this system involves basic QCD degrees of freedom at the nuclear level, in contrast with the usual description of the dynamics of the nuclear forces with phenomenological Lagrangians in terms of meson and nucleon degrees of freedom.

Due to the small size of charmonium at hadronic scale, its interaction with external gluon fields from interacting hadrons is expressed as a QCD multipole expansion [9] with higher order terms suppressed by powers of the quarkonium radius over the gluon wavelength, resulting in a long-distance effective theory that has been applied successfully at the leading order in many processes involving low-energy gluons [10]. The leading term in the expansion is the bilinear chromoelectric term, which is in fact the leading local gauge-invariant operator in an operator product expansion (OPE), whose matrix elements between hadronic states are evaluated using the trace anomaly [11,12]. This is a notorious example of a calculation where QCD matrix elements, otherwise untractable by perturbation theory, are determined by the symmetries of the theory.

Using nonrelativistic normalization of states and neglecting the charmonium recoil, the charmonium-nucleon amplitude can be written as a product of two matrix elements, one depending on the internal charmonium degrees of freedom and the other containing the external gluon fields [9]. After some color algebra the result is

$$f=-\frac{m_{\mathrm{red}}}{2\pi}\frac{2\pi}{3}\alpha_s\left\langle \varphi\left| r^i\frac{1}{H^{(8)}+\epsilon}r^j\right|\varphi\right\rangle\langle K_2|E_i^aE_j^a|K_1\rangle,$$

where $(H^{(8)}+\epsilon)^{-1}$ propagates the $c\bar{c}$ system in the octet

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state, $m_{\rm red}$ is the reduced mass of the proton-charmonium system, $\mathbf{K}$ its relative momentum, and φ is the internal charmonium wave function. Standard evaluation of the charmonium matrix element gives

$$f=-\frac{m_{\rm red}}{2\pi}d_2 a_0^3\left\langle\frac{1}{2}\mathbf{E}_a\cdot\mathbf{E}_a\right\rangle,$$

where $d_2=28\pi/27$ is the Wilson coefficient for a $1s$ charmonium state with Bohr radius a_0.

The field operator $\mathbf{E}^2$ is expressed as a linear combination of the gluonic contribution to the energy-momentum tensor $T^{\mu\nu}_{\rm gluonic}$ and the trace of the total energy-momentum tensor T^{μ}_{μ} through the scale anomaly [11,12] renormalized at the charmonium scale $\Lambda_Q\sim 1/a_0$. At zero momentum transfer the matrix elements of $T^{\mu\nu}_{\rm gluonic}$ and T^{μ}_{μ} are expressed in terms of the gluon-momentum fraction in the nucleon V_2 and the nucleon mass M, respectively. In this case the value of f equals the scattering length a_s and is given by

$$f=-\frac{m_{\rm red}}{2\pi}d_2 a_0^3\frac{M}{2}\left(\frac{3}{4}V_2(\Lambda_Q)-\frac{\alpha_s(\Lambda_Q)}{\beta(\alpha_s)}\right).$$

Using in the previous equation a value of $V_2=0.5$ from deep-inelastic scattering measurements, the hydrogenoid charmonium radius $a_0=1.6\ \mathrm{GeV}^{-1}$, the value of $\alpha_s=0.6$ for the strong coupling calculated at the scale Λ_Q, and the leading term for the Gell-Mann–Low beta function $-9\alpha_s^2/2\pi$, we find a value of $a_s=-0.2$ fm for the charmonium-proton scattering length, which agrees with the result obtained by Brodsky and Miller [8] from Ref. [12] using a parametrization of the strong coupling with freezing at low energies. The sign of the amplitude corresponds to an attractive interaction. Other results [13–15] differ widely because of different normalizations used in the calculation [16].

Scattering at low energies is described in terms of two parameters, the scattering length a_s, and the effective range $r_{\rm e}$. We use the value of the scattering length determined above, $a_s=-0.2$ fm, to describe the low energy charmonium-nucleon scattering. The value of the $c\bar{c}$-p effective range is unknown and cannot be obtained from the previous calculation, valid only at zero momentum transfer. We expect, however, a value for $r_{\rm e}$ between $a_0\simeq 0.3$ and 1 fm, which accounts for the small size of charmonium and the short range of the QCD van der Waals force. With these values, we compute the effect on the pp elastic amplitudes at the onset of charm threshold [5] and determine the binding energies of charmonium in nuclear matter [7,17]. Our results do not depend significantly on the value of $r_{\rm e}$.

The unitarity condition relates the imaginary part of an elastic scattering amplitude to a sum over all possible intermediate states that can be reached from the initial state. The enhancement to a given partial-wave amplitude T is determined by the analytic properties of the transition amplitude in the $\nu=p^2$ complex plane, with p the c.m.s. momentum, and is given by the dispersion integral [18]

$$T^{\rm enh}(\nu)=T(\nu)+\frac{1}{\pi}\int_0^\infty\frac{\mathrm{Im}\ T(\nu')}{\nu'-\nu-i\varepsilon}d\nu'.$$

We assume that the inelastic contribution of unitarity to the pp elastic scattering amplitude is dominated near threshold by the creation of a $pp\ c\bar{c}$ state with low relative momenta and internal quantum numbers $j=1$, $l=0$, which correspond to the $J=L=S=1$ quantum numbers of the pp system. The triplet wave has maximal spin correlation $A_{NN}=1$, and the pp orbital angular momentum must be odd since $c\bar{c}$ has negative intrinsic parity. The $pp\ c\bar{c}$ state is produced with partial width characterized by the measured branching ratio $B^{p\bar{p}}_{c\bar{c}}=0.0155$. The enhancement to the partial wave amplitude $T_{JJ}=T^{S=1}_{J=L}$ can be represented in the N/D form [19] in terms of the discontinuity of $T(\nu)$:

$$T^{\rm enh}_{JJ}(\nu)=\frac{1}{D(\nu)}\frac{1}{2\pi i}\int\frac{D(\nu')\mathrm{disc}\ \ T_{JJ}(\nu')}{\nu-\nu'}d\nu',$$

where the Jost function $D(\nu)$ is defined by [18]

$$D(\nu)=\exp\left[-\frac{1}{\pi}\int\frac{\delta(\nu')\ d\nu'}{\nu-\nu'-i\epsilon}\right]$$

in terms of the proton-proton-charmonium scattering s-wave phase shift $\delta(\nu)$ which, by unitarity, is the phase of the pp enhanced amplitude. We limit our calculation to the zeroth iteration $D=1$ in the previous integral, to obtain the determinantal approximation $T^{\rm enh}=T/D=RT$ with $R=D^{-1}$ the enhancement factor.

The pp elastic scattering is conveniently described in terms of the usual five helicity amplitudes $\phi_1=\langle++|\phi|++\rangle$, $\phi_2=\langle--|\phi|++\rangle$, $\phi_3=\langle+-|\phi|+-\rangle$, $\phi_4=\langle-+|\phi|+-\rangle$, and $\phi_5=\langle++|\phi|+-\rangle$. At large momentum transfer the PQCD quark interchange model (QIM) amplitudes [20] for proton-proton scattering dominate over quark annihilation and gluon exchange [21]. The helicity conserving amplitudes are related by $\phi_1^{\rm QIM}=2\phi_3^{\rm QIM}=-2\phi_4^{\rm QIM}$ and are the only nonvanishing at leading order [22]. We assume the same form for the QIM amplitudes as in Ref. [5] expressed in terms of the standard proton dipole form factor, consistent with nominal s^{-4} scaling law and angular distribution [1]. We do not consider any phase dependence on the QIM amplitudes since they cancel out in the present calculation.

Since the nominal power-law scaling for the scattering amplitude is not preserved individually by each partial wave, a modification of a given partial amplitude effectively breaks the s^{-4} scaling behavior of the total amplitude at the charm threshold. The partial wave expansion of the helicity amplitudes is expressed in terms of singlet, coupled, and uncoupled triplet amplitudes. Retaining the enhancement in the $J=L=S=1$ partial wave amplitude we need only to modify the $J=1$ wave in the uncoupled-triplet partial wave expansion [23]:

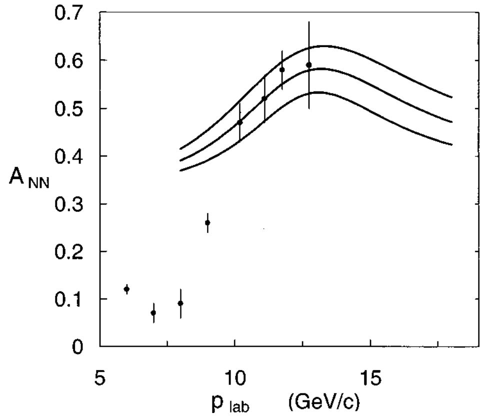

FIG. 1. A_{NN} as a function of p_{lab} at $\theta_{\mathrm{c.m.}}=90°$ near the charm threshold, where the model is applicable. The data is taken from Ref. [4]. The value of PQCD alone is 1/3. The upper, middle, and lower curves correspond to $r_{\mathrm{e}}=0.6$ fm, $r_{\mathrm{e}}=0.8$ fm, and $r_{\mathrm{e}}=1.2$ fm, respectively, and $a_s=-0.2$ fm.

$$\phi_3 \sim \sum_{J=\mathrm{odd}} (2J+1) T_{JJ}\, d^J_{11},$$

$$\phi_4 \sim -\sum_{J=\mathrm{odd}} (2J+1) T_{JJ}\, d^J_{-11},$$

with d^J the Wigner coefficients. The enhanced helicity amplitudes ϕ^{enh} expressed in terms of the QIM helicity amplitudes ϕ^{QIM}, the branching ratio $B^{pp}_{c\bar{c}}$, and the s-wave enhancement factor $R(\nu)$ are

$$\phi_1^{\mathrm{enh}} = \phi_1^{\mathrm{QIM}},$$

$$\phi_3^{\mathrm{enh}} = \phi_3^{\mathrm{QIM}} + 3B^{pp}_{c\bar{c}}(R-1)T_{11}d^1_{11},$$

$$\phi_4^{\mathrm{enh}} = \phi_4^{\mathrm{QIM}} - 3B^{pp}_{c\bar{c}}(R-1)T_{11}d^1_{-11},$$

where $T_{11}=\frac{1}{4}\int_{-1}^{+1}(d^1_{11}\phi_3^{\mathrm{QIM}} - d^1_{-11}\phi_4^{\mathrm{QIM}})dz$, and ϕ_2^{enh} and ϕ_5^{enh} are zero to leading order.

For the pp-$c\bar{c}$ state the s-wave phase shift is expressed in terms of the effective range approximation as $k\cot\delta=-1/a+\frac{1}{2}rk^2$, where $k=p-p_0$, with $p_0=2.32$ GeV/c the c.m.s. momentum corresponding to the charm threshold. In this approximation the Jost function is obtained directly from the phase shift [18] giving for the enhancement factor $R(k)=(k+i\alpha)/(k+i\beta)$, where α and β are related to the scattering parameters by $a=(\alpha-\beta)/\alpha\beta$ and $r=2/(\alpha-\beta)$. For definiteness we take $a=2a_s$, $r\sim r_{\mathrm{e}}$, assuming simple additivity in the interaction of charmonium with the external fields of the two protons. Comparison of the prediction for the spin correlation A_{NN} at $\theta_{\mathrm{c.m.}}=90°$ with the available data near the charm threshold, is shown in Fig. 1 for different values of r_{e}.

Since the QCD van der Waals force is attractive [7,12–15], it could lead to the formation of quarkonium bound to nuclei [7,17]. The discovery of such state would unveil the purely gluonic component of the strong forces, a genuine QCD effect at the nuclear level, which do not involve meson degrees of freedom. In fact, in the absence of valence light-quark exchange there is no one-meson standard nuclear potential and the contribution of higher-order intermediate meson states is negligible [8]. Furthermore, there is no short-range nuclear repulsion from Pauli blocking. In Ref. [7] an estimate of the QCD nucleon-charmonium van der Waals potential was obtained by rescaling the high-energy meson-nucleon interaction described by the Pomeron model [24], and determining the coupling and range of the interaction parametrized by the Yukawa form $V(r)=-\gamma e^{-\mu r}/r$ by adjusting the meson form factor in the Pomeron amplitude to describe the size of charmonium. The scattering length in the Born approximation $2\gamma m_{\mathrm{red}}/\mu^2 \simeq 0.5$ fm overestimates the strength of the interaction by almost a factor of 3 compared to the QCD nonperturbative result obtained above.

Due to the short range of the nuclear forces, additivity is not valid for all the nuclei but the very light and the interaction with charmonium depends on the nucleon distribution. Following Wasson [17], we write the charmonium-nucleus potential $V_{c\bar{c}\text{-}A}(r)$ at low energies as

$$V_{c\bar{c}\text{-}A}(r) = \int V_{c\bar{c}\text{-}N}(r-r')\rho(r')d^3r',$$

where $\rho(r)$ is the nucleon distribution in the nucleus of nucleon number A and $V_{c\bar{c}\text{-}N}(r)$ the charmonium-nucleon potential. Since the density in the central core of nuclei is practically constant, falling sharply at the edges, and the range of $V_{c\bar{c}\text{-}N}(r)$ is very short compared to the size of nuclei, the above expression for $V_{c\bar{c}\text{-}A}(r)$ is approximated by the nuclear matter result

$$V_{c\bar{c}\text{-}A} = \rho_0 \int V_{c\bar{c}\text{-}N}(r)d^3r = \frac{4\pi\rho_0 a_s}{2m_{\mathrm{red}}} = -11 \text{ MeV},$$

for $\rho_0=0.17$ fm^{-3} and m_{red} the $c\bar{c}$-N reduced mass, a result consistent with Ref. [12] and comparable with the binding energy of protons and neutrons in nuclear matter. For finite nucleus, we describe the nuclear density by the Fermi density function $\rho(r)=\rho_0/(1+e^{(r-c)/b})$ which fits very well the data and incorporates the thickness of the nuclear surface

TABLE I. Binding energies $\langle H\rangle$ of the η_c to various nuclei for a variational calculation corresponding to realistic nuclear densities [25] and a Gaussian form for the $c\bar{c}$-N interaction. The values of $\langle H\rangle$ are in MeV, the charmonium-nuclei reduced masses M_{red} are in GeV and the range of the potential R is in fm.

	M_{red}	$\langle H\rangle_{R=0.4}$	$\langle H\rangle_{R=0.8}$	$\langle H\rangle_{R=1.2}$
^{4}He	1.66	>0	>0	>0
^{6}Li	1.95	-0.12	-0.07	>0
^{9}Be	2.21	-1.31	-1.04	-0.68
^{12}C	2.36	-2.52	-2.02	-1.75
^{14}N	2.44	-3.31	-2.92	-2.54
^{40}Ca	2.77	-6.13	-5.83	-5.31
^{56}Fe	2.83	-6.70	-6.48	-6.23
^{208}Pb	2.95	-9.24	-9.20	-9.12

[25]. For the light nuclei we have used various forms for $\rho(r)$ found in the literature to describe the data [25]. We have investigated the binding of charmonium to various nuclei using different forms for $V_{c\bar{c}\text{-}N}(r)$ which reproduce the same scattering length $a_s = -0.2$ fm for various potential ranges. Consistent results were obtained for Yukawa, Gaussian, and Bargmann potentials. As an example, we give in Table I the results obtained for a Gaussian form $V(r) = V_0 e^{-(r/R)^2}$, with $a_s = \sqrt{\pi} m_{\rm red} V_0 R^3/2$.

We have determined the low-energy interaction of heavy quarkonium and nucleons using model-independent techniques based on the operator product expansion and the trace anomaly. The value of -0.2 fm for the $c\bar{c}$-nucleon scattering length corresponds to a total cross section of about 5 mb at threshold. This value reproduces the anomalous behavior of the spin correlation A_{NN} observed at $\sqrt{s} = 5$ GeV in pp elastic scattering at $\theta_{\rm c.m.} = 90°$ near the charm threshold, by the enhancement of pp amplitudes from the unitarity condition. The low-energy charmonium-nucleon interaction only depends on the short-range gluonic exchange properties of QCD between color singlet objects and do not involve meson degrees of freedom. Binding of charmonium was investigated for light, medium, and heavy nuclei using realistic nucleon distributions for various forms and ranges of the $c\bar{c}\text{-}N$ potential. Our results show that nuclear bound states of charmonium could be formed for $A \geqslant 6$. A value of about 10 MeV is found for the binding of charmonium in nuclear matter, which is comparable with the binding energy of nucleons, a remarkable result since the nucleon-nucleon interaction is two orders of magnitude stronger than the $c\bar{c}\text{-}N$ interaction. This is a consequence of the absence of Pauli blocking in the charmonium-nucleon system. Measurement of the J/ψ-nucleon scattering near threshold is important to determine the van der Waals strength since this reaction is dominated by gluon exchange [7]. The study of charmonium production close to threshold [26] and its interaction with nuclear matter [14] would provide a better understanding of the mechanisms of color dynamics.

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