Gluon gravitational form factors and mechanical properties of proton

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Inspired by the recent J/ψ photoproduction measurements, we discuss the gluon gravitational form factors (GFFs) and mechanical properties of the proton. This work presents a complete set analysis of gluon GFFs of the nucleon connecting the gluon part of energy-momentum tensor and the heavy quarkonium photoproduction. In particular, the gluon GFFs $A_J(t)$ and $D_J(t)$ are determined by a global fitting of the $J/\psi$ differential cross section experimental data. Combined with the quark contributions to the $D$-term extracted from the deeply virtual Compton scattering experiment, the total $D$-term are obtained to investigate their applications for the description of the mechanical properties. Specifically, the distributions of pressure and shear forces inside the proton have been presented. The proton mechanical radius, the mean square radius of the energy density, the pressure and energy density in the nucleon center are reported. These results provide a unique perspective for studying the proton gluon GFFs and important information for revealing the internal nature of nucleons.

I. INTRODUCTION

The form factor of nucleon provides critical information about many fundamental aspects of hadron structure. The charge and mass distribution are encoded in the electromagnetic form factors and gravitational form factors (GFFs), respectively [1–4]. Specifically, one can get a deeper understanding of the basic mechanical properties of the proton by studying the Druck term ($D$-term) GFFs [5, 6]. The sum of the quark and gluon contributions is a measurable quantity defined purely from the $D$-term, which encodes the information on shear forces and pressure distributions inside the proton. The quark $D$-form factor $D_q(t)$ has recently been extracted from the deeply virtual Compton scattering (DVCS) experiments and the pressure distribution inside the proton has been reported [7]. However, because the DVCS is almost insensitive to gluon, the gluon $D$-form factor is seldom extracted. The quark and gluon $D$-form factor parameterize the spatial-spatial components of the energy momentum tensor (EMT) and describe the internal dynamics of the nucleon system [8].

Recently, the quark $D$-form factor of the proton has been researched in the DVCS experiments and Lattice QCD [7–9], and the gluon $D$-form factor has also been studied theoretically in numerous frameworks. One work obtain the proton GFFs and investigate the mechanical properties using a light-front quark-diquark model constructed by the soft-wall AdS/QCD [10]. The nucleon form factors of the EMT are studied in the framework of the Skyrme model and in-medium modified Skyrme model [11, 12]. Reference [13] demonstrated the pressure, energy density and mechanical radius of the nucleon in light-cone QCD sum rule formalism. The EMT form factors of the nucleon within a $\pi - \rho - \omega$ soliton model are used to study the mechanical properties, such as pressure and energy density [14]. On the other hand, the distributions of pressure and shear forces inside the proton are investigated using lattice QCD calculations [8, 9], changing the little understanding situation about the gluon $D$-form factor.

At finite momentum transfer, the near-threshold heavy quarkonium photoproduction, such as $J/\psi$ and $\Upsilon$ meson, offer a superior path to access the gluon GFFs [2, 16–22]. These processes have gained quite an interest in recent years, because they promise to measure the naturalness of proton mass decomposition [20–24]. This work presents a connection between the gluon part of EMT and the near-threshold differential cross section of $J/\psi$. One reason is that the scalar gluon operator is dominant in the production amplitude of heavy quarkonium. Moreover, using heavy vector mesons photoproduction works because the high mass of $J/\psi$ defines a short distance interaction. In electroproduction the short distance is given by high $Q^2 >> 1$ GeV$^2$, i.e. high photon virtuality. This relation allows us to discuss the gluon GFFs by studying the near-threshold photoproduction data of heavy quarkonium.

Therefore, experimental information on vector meson photoproduction is essential to gain insight into the fundamental structure of the proton. Recently, the GlueX Collaboration reported the near-threshold cross section of the reaction $\gamma p \rightarrow J/\psi p$ [25]. The Jefferson Lab measured the differential cross section of $J/\psi$ on proton targets at a photon energy $E_\gamma$ from 9.1 GeV to 10.6 GeV [19], which is a near-threshold energy region. Those experimental data offer us a good window for studying the internal character of the proton. Presently, the Electron Ion Colliders (EIC) are claimed for probing the deepest structure inside the hadron and collecting $J/\psi$ data [26, 27]. High-precision experimental measurements are suggested to be performed at these facilities.

This paper is organized as follows. In Sec. II, the formulas of connecting the photoproduction and gluon GFFs, and the process of calculating the proton mechanical properties are provided. In Sec. III, the gluon GFFs are determined by fitting the $J/\psi$ photoproduction data. Then the computation result of the mechanical properties inside the proton are presented. A
II. FORMALISM

A. the photoproduction and gluon GFFs

In recent works [2, 16–22], it was suggested that the near-threshold differential cross section of heavy quarkonium photoproduction is sensitive to the gluon GFFs of the proton. Next, we will demonstrate the complete set analysis of gluon GFFs of the nucleon connecting the gluon part of the EMT and the J/ψ differential cross section.

The (00) component of the EMT defines the form factor in the Breit frame, which can be expressed as [23, 28, 29]

$$\langle P'|T_{00}|P \rangle = \bar{u}(P')u(P')G(t)$$  \hspace{1cm} (1)

where the spinor normalization $\bar{u}(P')u(P') = 2M$. For the proton, the $G(t)$ are parametrized as [23]

$$G(t) = MA_{q+g}(t) + \frac{t}{4M}B_{q+g}(t) - \frac{t}{4M}D_{q+g}(t)$$ \hspace{1cm} (2)

where $M$ is the proton mass. The form factors $A_{q+g}(t)$, $B_{q+g}(t)$ and $D_{q+g}(t)$ provide the mass distribution, the angular momentum distribution and the mechanical properties, respectively. In this paper, we mainly chuk the gluon contribution in GFFs to the $A_{g}(t)$ and $D_{g}(t)$ in the cross section calculations, as the fairly small contribution of $B_{g}(t)$ [10, 18, 30, 31]. Therefore, the component of the gluon part can be written as

$$\langle P'|T_{00}^g|P \rangle = 2M \cdot G_g(t) = 2M \left( MA_{g}(t) - \frac{t}{4M}D_{g}(t) \right)$$ \hspace{1cm} (3)

Usually, the differential cross section of the $J/\psi$ photoproduction is given by [2, 32]

$$\frac{d\sigma_{\gamma p \rightarrow J/\psi p}}{dt} = \frac{1}{64\pi W^2} \frac{1}{|p_{cm}|^2} |M_{\gamma p \rightarrow J/\psi p}|^2$$ \hspace{1cm} (4)

where $p_{cm}$ is the center of mass (c.m.) photon momentum in the $\gamma p \rightarrow J/\psi p$ process. $W$ and $t$ are the c.m. energy and the momentum transfer, respectively. The amplitude $M$ can be written as [2]

$$M_{\gamma p \rightarrow J/\psi p} = -Q_c c_2 2M \langle P'g^2T_{00}^g|P \rangle$$ \hspace{1cm} (5)

where $Q_c = 2e/3$ represents the coupling of the photon to the electric charge of the quarks in $J/\psi$ meson. $c_2$, the short-distance coefficient, is on the order of $\pi r_h^2$. $g^2 = 4$ is the QCD coupling with $\alpha_s \approx 0.32$ [21, 33]. Therefore, one can determine the $t$-dependence of the cross section to derive the gluon GFFs.

For the $A_{q+g}(t)$ form factor, the mass distribution of the proton are encoded in the $A$-form factor, which can be expressed under the dipole form parametrization as [8, 18]

$$A(t) = \frac{A_{q+g}(0)}{(1 - t/m_A^2)^2}$$ \hspace{1cm} (6)

where the constraint $A_{q+g}(0) = 1$ as the consequence of momentum conservation [5, 34]. Moreover, the gluon contribution $A_{g}(0) = 0.414$ was obtained from CT18 global QCD analysis [35], and basically coincident with other lattice QCD results [30, 36, 37]. The parameter $m_A$ in gluon A-form factor $A_{g}(t)$ is a free parameter fixed by differential cross section experimental data.

The D-form factor $D_{q+g}(t)$ is the most exciting one which has attracted considerable interest recently [5, 19]. The gluon D-form factor $D_{g}(t)$ is usually parameterized in the triple form and provided as [7, 38, 39]

$$D_{g}(t) = \frac{D_0}{(1 - t/m_D^2)^3}$$ \hspace{1cm} (7)

where $D_0$ and $m_D$ are the parameters adjusted to the experimental data. Note that $D_0$ is negative as the corresponding pressure distribution is found to be repulsive near the center of the nucleus.

The total energy density $T_{00}(r)$ in a hadron can be defined for the total system in Eq. 1. The gluon contribution of the energy density can be written as [5]

$$T_{00}^g(r) = \int d^3x T_{00}^g(r) = \int d^3x \left( T_{00}(r) + T_{00}^g(r) \right) = M \cdot A_{q+g}(0) = M$$ \hspace{1cm} (8)

It turns out that the form factor $G(t)$ in Eq. 2 at the momentum transfer $t = 0$ can be written as

$$G(0) = M$$ \hspace{1cm} (9)

Thus the proton mass radius can be defined through the derivative of the form factor $G(t)$ at $t = 0$ that [23]

$$\langle R_m^2 \rangle = \frac{6}{M} \left. \frac{dG(t)}{dt} \right|_{t=0} = 6 \left( 2 - \frac{D_{q+g}(0)}{4M^2} \right)$$ \hspace{1cm} (10)

Moreover, the gluon form factor $G_g(t)$ in Eq. 3 satisfies

$$G_g(0) = MA_g(0)$$ \hspace{1cm} (11)

Therefore, the coefficient $c_2$ can be determined by extracting the near-threshold differential cross section at $t = 0$, which can be written as

$$\frac{d\sigma_{\gamma p \rightarrow J/\psi p}}{dt} \bigg|_{t=0} = \frac{1}{64\pi W^2} \frac{1}{|p_{cm}|^2} |Q_c c_2 g^2 4M^3 A_g(0)|^2$$ \hspace{1cm} (12)

Finally, we construct the relation between the gluon GFFs and the differential cross section of heavy quarkonium photoproduction. The c.m. energy dependence caused by the differential cross sections at different photon energy can be regulated by $c_2$. Thus one can acquire stable and dependable gluon GFFs carrying much information on the proton mechanical properties.
B. proton mechanical properties

In contrast to the controversial gluon D-form factor, the quark D-form factor has recently been extracted from experiment. The sum of the quark and gluon form factors is a measurable quantity defined purely from the D-term, and one can get proton mechanical properties from the total D-term. Concretely, the quark D-form factor inside the proton is extracted by fitting the DVCS data [7]. One work determined the $D_q(t)$ as [5, 38]

$$D_q(t) = \frac{18}{25} \frac{d(0)}{(1 - t/M_0^2)^3}$$  \hspace{1cm} (14)

where the parameters are fitted to be $d(0) = -2, M_0 = 5\hbar c$ GeV [38].

The pressure $p(r)$ and shear forces $s(r)$ are “good observables” to report the pressure and shear forces distributions, which can be expressed as [5, 6]

$$s(r) = s_q(r) + s_g(r) = -\frac{1}{2} \frac{d}{dr} r \frac{d}{dr} \tilde{D}(r)$$  \hspace{1cm} (15)

$$p(r) = p_q(r) + p_g(r) = \frac{1}{2} \frac{d}{dr} r^2 \frac{d}{dr} \tilde{D}(r)$$  \hspace{1cm} (16)

Here $\tilde{D}(r)$ is the Fourier transform of $D_{q+g}(t)$ as [5, 6]

$$\tilde{D}(r) = \int \frac{d^3 \Delta}{2M(2\pi)^3} e^{-i \Delta r} D_{q+g}(0, \Delta^2) = \int \frac{d^3 \Delta}{2M(2\pi)^3} e^{-i \Delta r} \left(D_q(0, \Delta^2) + D_g(0, \Delta^2)\right)$$  \hspace{1cm} (17)

Note that the pressure distribution $r^2 p(r)$ satisfies the internal forces balance inside a composed particle [5]

$$\int_0^\infty dr \, r^2 p(r) = 0$$  \hspace{1cm} (18)

The normal and tangential forces in the composed particle system can be written as [5]

$$F_n(r) = \frac{2}{3} s(r) + p(r), \quad F_t(r) = -\frac{1}{3} s(r) + p(r)$$  \hspace{1cm} (19)

here the positive and negative eigenvalues correspond to “stretching” or “squeezing” along the corresponding principal axes, respectively. The normal and tangential force satisfy [5]

$$F_n(r) > 0, \quad \int_0^\infty 2\pi r \cdot F_t(r) dr = 0$$  \hspace{1cm} (20)

One can define the proton mechanical radius in term of the normal and tangential forces in the proton, which can be written as [5]

$$\left\langle R_{\text{mech}}^2 \right\rangle = \frac{\int d^3 r \, r^2 \left[ F_n^2(r) + F_t^2(r) \right]}{\int d^3 r \, F_n^2(r) + F_t^2(r)}$$  \hspace{1cm} (21)

$$= \frac{\frac{1}{M_0} \left( \frac{M_0}{M_0} + \frac{186(0)}{35M_0} \right)}{\frac{1}{M_0^2} \int_0^\infty D_s(t) \, dt + \frac{1}{4M_0^2} \int_0^\infty D_q(t) \, dt}$$

TABLE I. Obtained values of the parameters $m_A$, $m_D$ and $D_0$ by a global fitting of the differential cross section experimental data [19, 25], compared to the holographic QCD, the GPD+VMD approach and Lattice results [19, 22, 30, 40].

| approach                | $m_A$ (GeV) | $D_0$ | $m_D$ (GeV) |
|-------------------------|-------------|-------|-------------|
| Holographic QCD [19, 40] | 1.575       | -1.80 ± 0.528 | 1.21 ± 0.21 |
| GPD + VMD approach [19, 22] | 2.71 | -0.80 ± 0.44 | 1.28 ± 0.50 |
| Lattice QCD [19, 30] | 1.641       | -1.932 ± 0.532 | 1.07 ± 0.12 |

After calculating the form factors $A_{q+g}(t)$ and $D_{q+g}(t)$, the energy density and pressure in the nucleon center can be computed directly as [5]

$$T_{00}(r) = \frac{M}{4\pi r^2} \int_{-\infty}^0 dt \sqrt{-r} \left[ A_{q+g}(t) - \frac{r}{4M^2} D_{q+g}(t) \right]$$  \hspace{1cm} (22)

$$p(r) = \frac{1}{24\pi^2 M} \int_{-\infty}^0 dt \sqrt{-\pi} D_{q+g}(t)$$  \hspace{1cm} (23)

which are consistent with the illustration in Eqs. 8 and 16. The energy density satisfies $T_{00}(r) > 0$ in a mechanical system, this allows us to introduce the mean square radius of the energy density as [5]

$$\left\langle R_{E}^2 \right\rangle = \frac{\int d^3 r T_{00}(r)}{\int d^3 r T_{00}(r)} = 6 A_{q+g}(0) - \frac{3(D_0 + d(0))}{2M^2}$$  \hspace{1cm} (24)

This definition and the proton mass radius described in Eq. 11 coincide [23].

III. RESULTS AND DISCUSSION

The near-threshold differential cross section $d\sigma/dt|_{t=0}$ at different c.m. energy is determined in our previous work [4, 41]. Thus the short-distance coefficient $c_2$ can be well identified. By global fitting the GlueX and JLab experimental data [19, 25], the parameters $m_A$, $m_D$ and $D_0$ in gluon GFFs (Eq. 3) is extracted. The comparison between the differential cross section and the experimental measurements is manifested in Fig. 1, exhibiting a good agreement. The obtained values of the parameters $m_A$, $m_D$ and $D_0$ are also compared to the tiopele form results of holographic QCD, the GPD+VMD approach and Lattice QCD [19, 22, 30, 40], as listed in Table I. A slight larger $D_0$ and smaller $m_A$ and $m_D$ are extracted.

As shown in Fig. 2, the gluon D-form factor $D_q(t)$ (blue solid curve) is compared with the lattice QCD determinations [8, 9]. One find that the obtained gluon D-form factor in this work is smaller than the lattice QCD results in momentum transfer $|t| < 0.5$ GeV$^2$. Here the error of parameters $D_0$ and...
FIG. 1. Global fitting result of $\gamma p \rightarrow J/\psi p$ differential cross section as a function of $-t$ at c.m. energy $W = 4.25$ GeV, 4.28 GeV, 4.31 GeV, 4.35 GeV, 4.38 GeV, 4.41 GeV, 4.45 GeV, 4.48 GeV, 4.51 GeV, 4.54 GeV, 4.58 GeV. The blue band reflects an statistical error of $m_q$, $m_D$, and $D_0$. Reference of data can be found in [19, 25].

$m_D$ covers all the uncertainties of $D_4(t)$. By combining the quark contribution (red dashed curve) and gluon contribution in Fig. 2, it turn out that the parameter $D_4(0) = -2.08 \pm 0.25$ is overestimated to $D_4(0) = 1.44$ extracted by DVCS experiment, while $D_4'(0)$ is slightly larger than $D_4(0)$. Thus the generalized nucleon radius defined from the gluon GFFs is larger than quark counterparts.

The pressure and shear forces distributions inside the proton are obtained and displayed in Fig. 3. The red-dashed and blue-solid curve indicate the gluon and quark contributions of the pressure and shear forces distributions, respectively. The blue and green bands represent the uncertainties come from the error of the parameters $D_0$ and $m_D$. Here the positive sign means repulsion towards the outside, and the negative sign means attraction directed towards the inside. The total pressure and shear forces contributions for the sum of the quark and gluon contributions are illustrated as the green-dot-dashed curve in Fig. 3. It was found that the pressure is positive in the inner region, and negative in the outer region, with a zero crossing $r \approx 0.67$ fm, which shows the repulsive and binding pressures dominate in the proton are separated in radial space. Moreover, the shear forces distribution reaches its peak at $r = 0.63$ fm in our observation.

![Image](image_url)

FIG. 2. The comparison of the gluon $D$-form factor $D_g(t)$ (blue-solid curve) and the quark $D$-form factor $D_q(t)$ (red-dashed curve) extracted from DVCS experimental data [38]. Here the parameters $D_0 = -2.08 \pm 0.25$ and $m_D = 0.90 \pm 0.07$ GeV in $D_q(t)$ is applied. The blue band reflects an statistical error of $D_0$ and $m_D$. The black circles show the lattice QCD determinations of the gluon $D$-form factor [8, 9].

After discussing the gluon form factors $A_g(t)$ and $D_g(t)$, the gluonic energy density and pressure in the nucleon center can be computed from Eqs. 22 and 23. An important mechanical quantity $p_g(0)$ denotes the pressure of gluon contribution in the center of the nucleon of $1.27^{+0.86}_{-0.82}$ GeV/fm$^3$. Moreover, the energy density in the center of the nucleon is calculated to be $T^{(0)}_{00}(0) = 4.61^{+1.85}_{-1.95}$ GeV/fm$^3$. Actually, we have obtained a obviously large $p_g(0)$ and $T^{(0)}_{00}(0)$. The concrete comparison with other predictions are reported below.

One can add the quark contribution $p_q(0) = 1.39$ GeV/fm$^3$ and compute the system pressure $p(0) = 2.66^{+0.80}_{-0.52}$ GeV/fm$^3$ in the center of nucleon. Similarly, combining the energy density of quark contribution $T^{(0)}_{00}(0) = 6.93^{+1.87}_{-1.63}$ GeV/fm$^3$, we get the energy density in the nucleon center as $T^{(0)}_{00}(0) = 11.54^{+3.72}_{-3.58}$ GeV/fm$^3$. Moreover, the mean square radius of the...
energy density and proton mechanical radius are computed to be $0.68^{+0.04}_{-0.03}$ fm and $0.73 \pm 0.03$ fm, respectively. As listed in Table II, these proton mechanical quantities are compared with other existing theoretical results. As shown, our statements on the pressure and energy density differ with those predictions considerably [10, 12–14, 42, 43]. Actually, the quark contribution to the pressure and energy density are bigger than most of these references, regardless of the gluon contribution. The calculation of mechanical radius is comparable with Refs. [8, 13, 14, 42], while the mean square radius of the energy density is very near Ref. [12] within the error.

**IV. SUMMARY**

In this paper, one connects the near-threshold differential cross section of $J/\psi$ to the gluon GFFs. The gluon form factor $A_g(t)$ and $D_g(t)$ can be determined by connecting the gluon part of the EMT and the heavy quarkonium photoproduction. In particular, the parameters $m_t$, $m_D$ and $D_0$ in gluon GFFs are extracted by a global fitting of the $J/\psi$ differential cross section experimental data. All three gluon form factors $A_g(t), B_g(t)$ and $D_g(t)$, which are related to different components of the gluon GFFs, are resolved. One find that $D_g(t)$ is smaller than the lattice QCD results in momentum transfer $|t| < 0.5$ GeV$^2$. Combined with the quark $D$-form factor extracted from the DVCS experiment, the total $D$-term $D_{\psi+g}(t)$ are helpful for investigating their applications for the description of the mechanical properties. Correspondingly, the pressure and shear forces distributions inside protons from gluon and quark contributions are obtained. Subsequently, the proton mechanical radius defined by the $D$-term is estimated to be $0.73 \pm 0.03$ fm. The mean square radius of the energy density is computed to be $0.68^{+0.04}_{-0.03}$ fm. Moreover, The pressure and energy density in the center of nucleon are computed to be $2.66^{+0.52}_{-0.80}$ GeV/fm$^3$ and $11.54^{+3.72}_{-3.58}$ GeV/fm$^3$, respectively. It should also be noted that there are some discrepancies among the theoretical predictions on the mechanical properties. This paper contends that the central pressure and energy density exceed abundant previous expectations.

Because of the tripole form usually take in quark $D$-form factor [7, 8, 38], the tripole ansatz of the gluon $D$-form factor $D_g(t)$ is favorable to compare the gluon contribution with the quark contribution in $D$-term. Additionally, it may be feasible to achieve global fitting using artificial neural networks [44]. Thus the optimization of tripole form are necessary in the future research.

It has been suggested that the value of the proton charge radius and mass radius are [1, 2]

$$R_C = 0.8409 \text{ fm and } R_m = 0.55 \text{ fm}$$

The mean square radius of the energy density and mechanical radius we obtained lies near the middle of the charge radius and the mass radius [1, 2]. Generally, the measurements of the charge distribution and mass distribution, combined with measurements of the mechanical properties of the proton, will definitely advance our understanding of the origin of mass and proton structure. These research provide useful theoretical information for an in-depth understanding of proton mechanical properties.

The high-precision photo/electroproduction data of vector mesons is an important guarantee and basis for the accurate study of the internal structural properties of protons. We recommend that relevant experimental measurements be carried out in JLab [25] or EIC [26, 27] facilities.

**V. ACKNOWLEDGMENTS**

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TABLE II. The numerical values of mechanical quantities of nucleon, including the proton mechanical radius, the mean square radius of the energy density, the energy density and pressure in the center of the proton, compared with other predictions from different approaches.

| Approaches and Models | \( p(0) \) (GeV/fm\(^3\)) | \( T_{\text{xx}}(0) \) (GeV/fm\(^3\)) | \( \sqrt{\langle R_{\text{mech}}^2 \rangle} \) (fm) | \( \sqrt{\langle R_p^2 \rangle} \) (fm) |
|----------------------|-----------------|----------------|-----------------|-----------------|
| light-front quark-diquark model (1) [10] | 0.29 | 3.21 | 0.86 | - |
| light-front quark-diquark model (2) [10] | 0.40 | 4.58 | 0.86 | - |
| light-front quark-diquark model (2D LF) [43] | 0.354 | 1.54 | 0.50 | 0.46 |
| light-front quark-diquark model (3D BF) [43] | 4.76 | 2.02 | 0.50 | 0.57 |
| Skyrme model [12] | 0.26 | 1.45 | - | 0.65 |
| light-cone QCD (1) [13] | 0.67 | 1.76 | 0.73 | - |
| light-cone QCD (2) [13] | 0.62 | 1.74 | 0.72 | - |
| lattice QCD at leading order [42] | 0.84 | 0.92 | 0.72 | - |
| lattice QCD (modified z-expansion) [8] | - | - | 0.71 | - |
| lattice QCD (tripole ansatz) [8] | - | - | 0.75 | - |
| \( \pi - \rho - \omega \) soliton model [14] | 0.58 | 3.56 | - | 0.82 |
| this work | 2.66\(^{+0.90}_{-0.52}\) | 11.54\(^{+3.72}_{-3.58}\) | 0.73 \(\pm\) 0.03 | 0.68\(^{+0.04}_{-0.03}\) |

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