First extraction of proton mass radius and scattering length $|\alpha_{\rho p}|$ from $\rho^0$ photoproduction

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As the lightest physical states excited from the vacuum by the scalar gluon, near-threshold $\rho^0$ photoproduction is considered to be a suitable way to extract proton mass radius and scattering lengths of $\rho^0$ and proton interaction. In this work, under the assumption of the scalar form factor of dipole form, the value of proton mass radius is calculated as $0.86 \pm 0.08$ fm by fitting the differential cross section of $\gamma p \rightarrow \rho^0 p$ reaction at near-threshold energy $W = 1.78$ GeV. Moreover, the value of $\rho^0$-proton scattering length $\alpha_{\rho p} = 0.29 \pm 0.07$ fm is obtained for the first time within the vector meson dominance model. These results may provide useful theoretical information for an in-depth understanding of proton structure and its interaction with vector mesons.

I. INTRODUCTION

A precise determination of $\rho^0(770)$ photoproduction at the near-threshold energies has been motivated by several aspects. First, mentioned in Ref. [1] that the $\rho^0$ meson, as the lightest physical states excited from the vacuum by the scalar gluon, its near-threshold photoproduction is regarded as one golden process to research the mass distribution inside the proton. Furthermore, since the same the vector quantum numbers as photon which is $J^{PC} = 1^{--}$, the behavior of the near-threshold cross section can be related to vector meson-proton ($Vp$) scattering length [2]. It is expected to be possible to extract the $\rho^0$-hadron scattering length from the near-threshold cross section of $\rho^0$ photoproduction, and then determine the $\rho^0$ binding energy in nuclear matter. Moreover, theoretical studies indicate that the near-threshold vector mesons photoproduction will give access to many interesting physics aspects, such as trace anomaly contribution to the nucleon mass, cusp effects and so on [3, 4].

The proton geometrical radius is a big inspiration in understanding the proton structure, and it can be measured by using lepton as a probe. The most studied proton charge radius was obtained by colliding the nucleus with high-energy electron. The electromagnetic form factors provide necessary information about the distribution of electric charge [5, 6]. On the experimental side, the proton charge radius was determined as $0.8409 \pm 0.0004$ fm [7] from elastic electron scattering experiments. In addition to charge radius extracted from the electromagnetic form factors, the mass radius reflects the mass distribution of the proton, which is a fundamental property of the proton [1]. However, little information about proton mass radius is explicit at present. Since the interaction of gravitons and proton scattering is very weak, far beyond the measurement limit of current experiments. Therefore, it is difficult to measure the proton mass radius experimentally. Actually, the gravitational form factors (GFFs) are helpful for us to understand the perturbative and nonperturbative quantum chromodynamics (QCD) effects, providing a connection to the spatial distribution of quarks inside the proton [8–10]. In QCD theory, the photoproduction of a quarkonium off the proton is connected to the scalar GFFs, which are sensitive to the proton mass distribution from the quantum chromodynamics trace anomaly [9, 11]. Under an assumption of the scalar form factor of dipole form, the proton mass radius can be extracted via the near-threshold photoproduction of vector meson differential cross section [1, 12]. Moreover, our previous work [13] shows that extracting proton mass radius from the near-threshold differential cross section of heavy quarkoniums is always affected by large $|\alpha_{\text{min}}|$. And if the proton mass radius is extracted from the lighter vector meson photoproduction data, the effect from $|\alpha_{\text{min}}|$ is much smaller. Thus as a much lighter meson, the $\rho^0$ photoproduction process may be an ideal choice to calculate the proton mass radius from this perspective.

The evaluation of the scattering lengths may serve as a unique input for QCD-motivated models of vector meson-nucleon interactions [14–17]. The behavior of the near-threshold cross section is related to $Vp$ scattering length [2]. Provided in the Vector Meson Dominance (VMD) model [4, 18], scattering lengths for $\omega p, \phi p, J/\psi p, \psi(2S)p$ and $Tp$ reactions have been reported using the recent photoproduction experiment data or quasi data [14–17, 19]. Since the VMD model does not contain free parameters in the process from $\gamma p$ to $Vp$ reaction. It is superior for us to obtain qualitative estimates when extracting scattering lengths $|\alpha_{Vp}|$. One find that these scattering lengths $|\alpha_{Vp}|$ satisfy an increase with the meson’s mass $m_V$ by comparing the several literature [14–17, 19]. A convictive argument is that the size of the scattering length is related to the radius of the vector meson, which can be written as $r_{qi} \approx 1/(2m_q)$. As the lighter state compared with the previous research, it is of great interest to wonder if the scattering lengths $|\alpha_{\rho p}|$ can break the maximum boundary of scattering length $|\alpha_{Vp}|$. Therefore, This work will allow us to provide more theoretical reference for future studies on characterizing the vector meson-proton scattering length by learning the near-threshold photoproduction of vector mesons.

On the experimental side, the SAPHIR Collaboration reported the $\rho^0$ photoproduction total cross section at center of mass (c.m.) energy up to $W = 2.36$ GeV and the lowest en-
ergy of differential cross section is 1.78 GeV [20], which is a near-threshold energy. More experimental information on $\rho^0$ photoproduction is essential to gain insight into the interior character of the proton and $\rho^0 p$ scattering length. Nowadays, the JLab experiment are suggested to be built for probing the deepest structure inside the hadron and collecting $\rho^0$ data. The high precision experimental measurements are suggested to be carried out on this facility [21].

The paper is organized as follows. The process of extracting proton mass radius are provided in Sec.II, some analysis of the result is presented. Then in Sec. III, the formalism of scattering length $a_{\gamma p}$ from cross section is introduced, the results and discussion are also reported. A comparative analysis with the scattering lengths for $\omega p$, $\phi p$, $J/\psi p$, $\psi(2S)p$ and $\Upsilon p$ are suggested. A short summary is given in Sec. IV.

II. SCALAR GFFS AND MASS RADIUS

Using the standard form, the differential cross section of the $\rho^0$ photoproduction can be written as [1, 7]

$$\frac{d\sigma_{\gamma p \to \rho^0 p}}{dt} = \frac{1}{64\pi W^2} \frac{1}{|\mathbf{p}_{\gamma\pi}|^2} |M_{\gamma p \to \rho^0 p}(t)|^2$$

where $\mathbf{p}_{\gamma\pi}$ is the photon momentum of the $\gamma p \to \rho^0 p$ process; $W, t$ is the c.m. energy and momentum transfer, respectively. Ref. [1] writes the amplitude $M$ in terms of the scalar GFFs as

$$M_{\gamma p \to \rho^0 p} = -i(Q_u + Q_d)e\frac{16\pi^2 M}{b} \langle P | T | P \rangle$$

where $b = 9$ for three light quarks $u, d$ and $s$. $Q_u$ and $Q_d$ represent the coupling of the photon and the quarks in $\rho^0$ meson. We take a superposition of the amplitudes with $Q_u$ and $Q_d$ weighted by the $\rho^0$ wave-function, and obtain an effective $Q_{\text{quark}} = (Q_u - Q_d)/\sqrt{2} = (1/\sqrt{2})c_2$ the short-distance coefficient, and is on the same order of magnitude as $\pi r^2_q$. The radius of the $q\bar{q}$ pair is $r_{q\bar{q}} \approx 1/(2m_q)$, with $m_q = m_u = m_d = 0.33$ GeV [22]. Finally the value of $c_2$ is on the order of $r^2_{q\bar{q}} = 0.28$ fm$^2$. Then we will check the value of $c_2$ in the subsequent calculation.

In the weak gravitational field approximation, the proton mass radius is defined through the form factor of the energy-momentum tensor (EMT) of QCD [1, 23]. The scalar GFFs are usually parameterized as the dipole form and provided as [1]

$$G(t) = \frac{G(0)}{1 - t/m^2_r}$$

where $G(0) = M$ and $m_r$ is a parameter adjusted to the experimental data. Combining the scalar GFFs $\langle P | T | P \rangle = G(t)$, Eq.2 and Eq.3, the differential cross section of $\gamma p \to \rho^0 p$ reaction can be determined by fitting the SAPHIR data [20]. In this work, the differential cross-section at the lowest incident-photon energy $E_\gamma = 1.225$ GeV ($W = 1.78$ GeV) in the current experiment is used to determine the parameters in Eq.1. Then the free parameters $c_2$ and $m_r$ are fixed by fitting the near-threshold differential cross section with the value of $\chi^2/$d.o.f. is 0.61. The comparison between the differential cross section and the experimental measurements is manifested in Fig.1, exhibiting a good agreement.

The extracted short-distance coefficient $c_2 = 0.88 \pm 0.09$ fm$^2$ is on the order of $\pi r^2_q$, which coincides with our expectation. Note that, compared to the extracted value $c_2 = 0.207$ fm$^2$ from $J/\psi$ GlueX data [1], the short-distance coefficient extracted from $\rho^0$ data is larger. The parameter $m_r$ is a more important physical quantity in this work. We perceive that the mass radius $R_m$ of the nucleon can be defined in terms of the scalar GFFs as [1, 24]

$$\langle R^2_m \rangle = \frac{6}{G(0)} \frac{dG(t)}{dt} \bigg|_{t=0} = \frac{12}{m_r^2}$$

The fitted result provide critical information about the distribution of mass in proton that $m_r = 0.79 \pm 0.08$ GeV corresponding to the mass radius $R_m = 0.86 \pm 0.08$ fm. To avoid dependence on a single energy point, we also compare our work with other results by extracting differential cross section experimental data in c.m. energy $W = 1.82$ GeV, 1.87 GeV, 1.94 GeV [20] and 1.92 GeV [25]. The fitted results are manifested in Fig.2, compared with several experimental data [20, 25]. Finally the root-mean-square (rms) mass radius of the all fitted result is calculated as 0.91 $\pm$ 0.09 fm, which is shown in the black dashed curve in Fig.3. If the error bar is considered, the rms mass radius is comparable to the result extracted from the differential cross section at c.m. energy $W = 1.78$ GeV.

According to Kharzeev’s calculation by fitting the GlueX data of $J/\psi$ photoproduction [26], the mass radius is calculated to be $0.55 \pm 0.03$ fm [1]. Moreover, one work [27] obtain the average mass radius is $0.67 \pm 0.10$ fm by extracting the $\phi$ experimental data [28] and $0.68 \pm 0.03$ fm by extracting the $\omega$ photoproduction data [29], respectively. Compared with these results by extracting $\omega, \phi$, and $J/\psi$ photoproduction, our work for the mass radius is much larger and close to the charge radius of proton.

Then we try to describe the mass distribution inside the proton. The Fourier transform of the scalar GFFs $G(t)$ can be written as [30, 31]

$$\tilde{D}(r) = \int \frac{d^3 \Delta}{(2\pi)^3} e^{-i\mathbf{r}\cdot\mathbf{\Delta}} G(-\mathbf{\Delta}^2)$$

where $-\mathbf{\Delta}^2 = t$. Finally the mass distribution $\tilde{D}(r)$ inside the proton is derived from $G(t)$ as shown in Fig.4. Here the parameters $c_2$ and $m_r$ in Eqs.1, 2 and 3 is applied by fitting the $\rho^0$ photoproduction data at $W = 1.78$ GeV. It can be seen that the mass distribution is the largest at the center of the proton and than exponential decreases.
III. SCATTERING LENGTH $|\sigma_{\rho p}|$

The $\rho^0 p$ scattering length is related to the near-threshold photoproduction of $\rho^0$ meson. In this paper, the VMD model is used to connect the reaction $\gamma p \to \rho^0 p$ and $\rho^0 p \to \rho^0 p$. Applying the effective VMD approach, the near-threshold cross section during the elastic scattering processes becomes \(^{(4, 32)}\)

$$d\sigma \over dt_{\text{thr}} = {\alpha \pi^2 \over |p_{\text{cm}}|^2 s_{\rho^0}} \left| {d\sigma_{\rho^0 p \to \rho^0 p} \over d\Omega} \right|_{\text{thr}}$$

$$= {\alpha \pi^2 \over |p_{\text{cm}}|^2 s_{\rho^0}} \left| |\sigma_{\rho^0 p}|^2 \right|$$

(6)

here the VMD coupling constant $g_{\rho^0}$ is deduced from the leptonic decay width $\Gamma_{\rho^0 e^-}$ as \(^{(17)}\)

$$g_{\rho^0} = \sqrt{\alpha \pi^2 m_{\rho^0} \rho_{\rho^0}} \over \sqrt{3} \Gamma_{\rho^0 e^-}$$

(7)

here $\Gamma_{\rho^0 e^-} = 7.04$ keV from Particle Data Group \(^{(7)}\), so $g_{\rho^0} = 2.47$ is got for $\rho^0$ meson. If setting $d\sigma \over dt_{\text{thr}} = b_1$, the scattering length $|\sigma_{\rho^0 p}|$ is given as

$$|\sigma_{\rho^0 p}| = g_{\rho^0} |p_{\text{cm}}| \sqrt{b_1 \over \alpha}.$$  

(8)

Note that, $b_1$ and $|p_{\text{cm}}|$ must satisfy the conditions that obtained from the threshold.

According to the fitted result in Figs.1 and 2, the differential cross section of the $\rho^0$ photoproduction in Eq.1 can be obtained. Thus the rms $\rho^0 p$ scattering length can be estimated to be $|\sigma_{\rho^0 p}| = 0.29 \pm 0.02$ fm, as shown in Fig.5.

The scattering length $|\sigma_{\rho^0 p}|$ can also be expressed by total photoproduction cross section \(^{(19)}\)

$$|\sigma_{\text{thr}}| = R \cdot {4 \alpha \pi^2 \over s_{\rho^0}^2} \cdot |\sigma_{\rho^0 p}|^2$$

(9)

where $R$ is the ratio between the initial c.m. momentum $|p_{\text{cm}}|$.
and the final momentum \(|p_{cm}|\). As the function of c.m. energy, \(R(W)\) has a range of \(R(W) \in [0, 1]\) and is positively correlated with the c.m. energy. Combining Eq. (9) and (7), scattering length \(|\alpha_{p^0p}|\) is given as

\[
|\alpha_{p^0p}| = \frac{g_{p^0}}{2\pi} \sqrt{\frac{\sigma(R)}{\alpha R}}.
\]

We extract the scattering length from the total cross section SAPHIR data at an energy region \(W \in [1.72 \text{ GeV}, 2.02 \text{ GeV}]\) using Söding, Ross-Stodolsky and Berit-Winger method [25], as shown in the green-squares in Fig. 5. The rms value of scattering length of proton and \(p^0\) is calculated as 0.29 ± 0.01 fm, which is consistent to the result extracted from the differential cross section. Finally, the value of \(p^0\)-proton scattering lengths \(a_{p^0p} = 0.29 \pm 0.07\) fm is obtained considering the error bars of all the result.

Based on the recent threshold measurements of the photoproduction of \(\omega\) and \(\phi\) mesons off the proton by the A2 (MAMI) [14] and CLAS (JLab) [33], one can determine vector meson proton scattering lengths \(|\alpha_{\omega p}|\) and \(|\alpha_{\phi p}|\) using the VMD model [14, 15]. What is more, the absolute value of the \(T\) scattering length is studied using quasi data generated from the QCD model [16, 34]. In our previous work [19], the \(J/\psi p\) and \(\psi(2S)p\) scattering lengths are studied systematically. Finally, the relationship including \(\omega, \phi, J/\psi, \psi(2S), \) and \(T\) can be determined as

\[
|\alpha_{Tp}| \leq |\alpha_{\psi(2S)p}| \leq |\alpha_{J/\psi p}| \leq |\alpha_{\phi p}| \leq |\alpha_{\omega p}|.
\]

Note that, the scattering length \(|\alpha_{p^0p}|\) is not follow the rule in Eq. 11, as shown in Fig. 6. The main reason is the broad width of \(p^0\). For example, \(\omega\) and \(p^0\) have close branching ratios, whereas the total width of \(p^0\) is more than 10 times larger than that of the \(\omega\).

Using the QCD sum rule, one work [35] gets the absolute value of the \(p^0\) scattering length as 0.47 ± 0.05 fm. In fact, if the error is considered, our results are close to the prediction of the QCD sum rule.

**FIG. 4.** 2D plot of the mass distribution inside the proton from the Fourier transform of the GFFs \(G(t)\).

**FIG. 5.** The obtained scattering length of \(p^0\)-proton interaction. Here the red-pentagon and blue-circle are extracted from Refs. [20, 25]. The green-squares show the results derived from SAPHIR total cross section data [25]. The light blue band reflect the region of \(\alpha_{p^0p}\).

**FIG. 6.** Comparison of the scattering lengths \(|\alpha_{p^0p}|\) as a function of the inverse mass of vector mesons, including \(\rho^0, \omega, \phi, J/\psi, \psi(2S), \) and \(T\). The magenta-pentagram show the \(p^0\) scattering length from this work. The blue-rhombus shows the analysis of \(\rho^0, \omega, \phi, \) and \(T\) [14–16]. The blue-squares shows the \(J/\psi p\) and \(\psi(2S)p\) scattering lengths from two gluon exchange model [19]. The red-solid line is hypothetical [16].

**IV. SUMMARY**

In this paper, the proton mass radius and scattering length \(|\alpha_{p^0p}|\) are extracted for the first time by fitting the experimental data of rho meson photoproduction. The value of mass radius is calculated as 0.86 ± 0.08 fm from the differential cross section at near threshold c.m. energy \(W = 1.78\) GeV, which is basically consistent with the rms value obtained by fitting several other near-threshold experimental data of \(p^0\) photoproduction.
duction. One find that the proton mass radius extracted from the rho meson photoproduction is larger than the other results extracted by $\omega, \phi$, and $J/\psi$ photoproduction, but is close to the proton charge radius. Unlike heavy quarkonium, for $p^0$ meson, one may no longer assume the dominance of the scalar gluon operator in the production amplitude, as the light quark operators should give large contribution. This may be the reason why the extracted radius is larger and closer to the charge radius dominated by quarks.

Further, under the framework of VMD model, the value of $p^0$-proton scattering length is calculated to be $|a_{p^0|p}| = 0.29 \pm 0.07$ fm. Apparently, the scattering length $|q_{p^0|p}|$ is not follow the rule that the scattering length satisfies an increase with the meson’s mass. The deviations can be attributed to the large width of $p^0$ decay.

Our results should provide an important numerical reference for subsequent research in this area. Moreover, due to the the large error of SAPHIR data we use, more high-precision experimental measurement data is very much needed, which can be realized in the JLab experiment [21].

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