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We show that the QCD van der Waals attractive potential is strong enough to bind a ϕ meson onto a nucleon inside a nucleus to form a bound state. The direct experimental signature for such an exotic state is proposed in the case of subthreshold ϕ meson photoproduction from nuclear targets. The production rate is estimated and such an experiment is found to be feasible at the Jefferson Laboratory.

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It has been suggested [1] that the QCD van der Waals interaction, mediated by multi-gluon exchanges, is dominant when the interacting two color singlet hadrons have no common quarks. In fact, the QCD van der Waals interaction is enhanced at low velocity as has been shown by Luke, Manohar, and Savage [2]. This finding supports the prediction that a nuclear-bound quarkonium can be produced in charm production reactions at threshold, and the interpretation that the structures seen in $s^{10}d\sigma/dt(pp \rightarrow pp)$ and the A_{NN} spin correlation at $\sqrt{s} \sim 5$ GeV and large c.m. angles [3] can be attributed to $c\bar{c}uudud$ resonant states [4]. If these interpretations are correct, then analogous effects could also be expected at the strangeness threshold. The objective of this Rapid Communication is to explore this possibility.

We are motivated by the investigation of the nuclear-bound quarkonium by Brodsky, Schmidt, and de Téramond [1]. They used a nonrelativistic Yukawa-type attractive potential $V_{(Q\bar{Q})A} = -\alpha e^{-\mu r}/r$ characterizing the QCD van der Waals interaction. They determined the α and μ constants using the phenomenological model of high-energy Pomeron interactions developed by Donnachie and Landshoff [5]. Using a variational wave function $\Psi(r) = (\gamma^3/\pi)^{1/2} e^{-\gamma r}$, they predicted bound states of η_c with ${}^3\text{He}$ and heavier nuclei. Their prediction was confirmed by Wasson [6] using a more realistic $V_{(Q\bar{Q})A}$ potential taking into account the nucleon distribution inside the nucleus.

Similarly, one expects the attractive QCD van der Waals force dominates the ϕ -N interaction since the ϕ meson is almost a pure $s\bar{s}$ state. It is possible that a ϕ -N bound state or resonant state can be formed in some reactions. In photoproduction of ϕ meson from a proton target above threshold, the formation of a bound ϕ -N state is not likely because of the momentum mismatch between the ϕ and the recoil proton. As such, no experimental evidence exists on the formation of the ϕ -N bound state up to now. On the other hand, such a ϕ -N bound state could be formed inside a nucleus. In this Rapid Communication, we will verify this possibility and make predictions for future experimental tests.

Using the variational method and following Ref. [1] to assume $V_{(s\bar{s})N} = -\alpha e^{-\mu r}/r$, we find that a bound state of ϕ -N is possible with $\alpha = 1.25$ and $\mu = 0.6$ GeV. The binding energy obtained is 1.8 MeV. Our results should be compared with $\alpha = 0.6$ and $\mu = 0.6$ GeV determined by Brodsky, Schmidt, and de Téramond [1] for the $c\bar{c}$ quarkonium. The

interaction is expected to be enhanced by $(m_c/m_s)^3$, i.e., $q\bar{q}$ separation cubed, from $c\bar{c}$ to $s\bar{s}$. Since the radius of the ϕ meson is (0.4 fm [7]) twice the radius of the J/Ψ meson, $\alpha = 1.25$ is a rather conservative coupling constant to use for the ϕ -N interaction. Also, the interaction is expected to have longer range for the ϕ -N system than that of the $c\bar{c}$ -N interaction. Thus, $\mu = 0.6$ GeV used in the variational approach described above is also conservative for the ϕ -N interaction. Further, this attractive force is enhanced inside the nucleus in the quasifree subthreshold photoproduction kinematics. Hence, a bound state of ϕ -N is possible from the attractive QCD van der Waals force. Our qualitative finding can be verified on the lattice in the future [8].

Experimentally, it is possible to observe the formation of a bound state ϕ -N in the subthreshold quasifree ϕ photoproduction process. The incoming photon couples to a moving nucleon inside the nucleus. The ϕ meson can be produced near rest inside the nuclear medium in the laboratory frame when the initial nucleon is moving in a direction opposite to that of the incoming photon. The attractive QCD van der Waals force between the ϕ meson and nucleons inside the residual nuclear system enhances the probability for the formation of the ϕ -N bound state. It is thus possible for a bound state ϕ -N to be formed inside the nucleus in the quasifree subthreshold ϕ production process from a nuclear target. The experimental search for such a bound state would be a triple coincidence detection of kinematically correlated K^+ , K^- , and proton in the final state. The momentum distributions of these final state particles are different from those from unbound quasifree ϕ production and the direct quasifree K^+K^- production. Thus, it is possible to identify a bound ϕ -N state experimentally using the above mentioned triple coincidence measurement. Such an experiment is feasible at Jefferson Laboratory where advantages of the continuous-wave electron beam, high luminosity, and the state-of-the-art detector package will be utilized to their full capabilities. The rate estimate for such a measurement is described below.

We assume that the photoproduction of a ϕ -N bound state, called d , from nuclei is a two-step process and can be evaluated in the impulse approximation. The reaction mechanism is illustrated in Fig. 1. We consider the production on a p -shell nucleus, such as ${}^{12}\text{C}$, and assume that its structure can be described by the simple shell model with harmonic oscillator wave functions. By using the closure to sum over

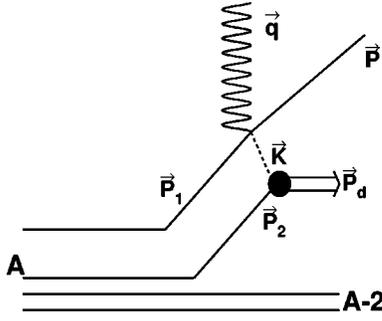


FIG. 1. The graphical representation of the quasifree process discussed in the text.

the intermediate $(A-1)$ -nucleon states, the reaction amplitude for $A_i(\gamma, d)A_f$ can be written in the rest frame of the initial nucleus A_i as

$$\begin{aligned}
 T_{fi}(p_d, p_2; q, E) &= \int d\vec{k} \left[\sum_{\alpha \neq \beta} \phi_\alpha(\vec{p} + \vec{k} - \vec{q}) \phi_\beta(\vec{p}_d - \vec{k}) \right] \\
 &\quad \times F(p_d; k, (p_d - k)) \\
 &\quad \times \frac{1}{E - E_{A-1}(\vec{q} - \vec{p} - \vec{k}) - E_\phi(k) - E_N(p) + i\epsilon} \\
 &\quad \times t(k, p; q, (p + k - q)), \quad (1)
 \end{aligned}$$

where $E_\alpha(k) = [m_\alpha^2 + \vec{k}^2]^{1/2}$ is the energy for the particle α with momentum \vec{k} , $t(k, p; q, p_1)$ is the amplitude for the $\gamma(q) + N(p_1) \rightarrow \phi(k) + N(p)$ transition, $F(p_d; k, p_2)$ is for the $\phi(k) + N(p_2) \rightarrow d(p_d)$ transition, and $\phi_\alpha(p)$ is the normalized harmonic oscillator wave function. The total energy is $E = E_i + q$, and E_i denotes the energy of the initial nucleus. Noting that $p_1 = p + k - q$ and $p_2 = p_d - k$, Eq. (1) can be easily identified with Fig. 1.

We consider the energies near and below the ϕ production threshold. It is then reasonable to assume that the intermediate ϕ - N is in s wave and its transition matrix elements can be simplified as

$$t(k, p; q, p_1) \sim \frac{1}{4\pi} t_0(Q, q_c), \quad (2)$$

where $t_0(Q, q_c)$ is the on-shell $\gamma N \rightarrow \phi$ - N amplitude in the center-of-mass frame of the γN subsystem, q_c is the relative momenta of the γN subsystem, and Q is the relative momentum of the ϕ - N subsystem. We can estimate $t_0(Q, q_c)$ from the total cross section of $\gamma N \rightarrow \phi$ - N defined by

$$\sigma^{\text{tot}}(\omega) = \frac{4\pi}{q_c^2} \rho_Q |t_0(Q, q_c)|^2 \rho_{q_c}, \quad (3)$$

where $\omega = q_c + E_N(q_c) = E_\phi(Q) + E_N(Q)$, the density of states are $\rho_{q_c} = \pi q_c^2 E_N(q_c) / (q_c + E_N(q_c))$ and $\rho_Q = \pi Q E_\phi(Q) E_N(Q) / (E_N(Q) + E_\phi(Q))$. We use the $\sigma^{\text{tot}}(\omega)$ predicted by the model of Ref. [9] which was constructed to

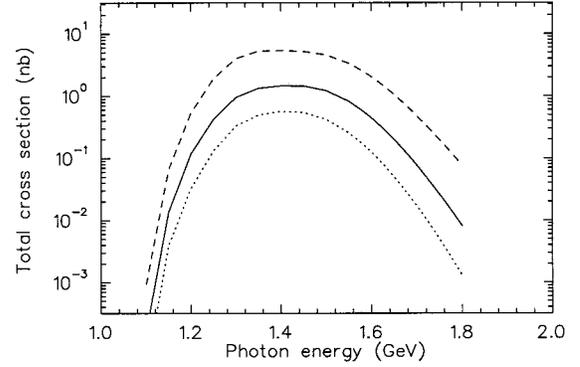


FIG. 2. The calculated total cross section for the formation of the ϕ - N bound state as a function of the photon energy. The dashed, solid, and dotted curves are for $\Lambda = 2, 3, 4$ fm, correspondingly.

fit the available data. We find that the $\sigma^{\text{tot}}(\omega)$ from threshold up to about 1.7 GeV can be fitted by $t_0(Q, q_c) \sim 0.5 \times 10^{-8} (\text{MeV})^{-2}$.

For an s -wave intermediate ϕ - N state, the $\phi N \rightarrow d$ amplitude can be written

$$\begin{aligned}
 F(p_d; k, p_2) &= \frac{\sqrt{4\pi}}{(2\pi)^{3/2}} \\
 &\quad \times \int r^2 dr \frac{\sin(Q'r)}{Q'r} [e^{-\Lambda^2 Q'^2} V_{(s\bar{s})N}(r)] \Psi(r), \quad (4)
 \end{aligned}$$

where Q' is the relative momentum of the ϕ - N subsystem, the van der Waals potential $V_{(s\bar{s})N}(r)$ and the normalized wave function $\Psi(r)$ for the bound state d have been determined from a variational calculation, as discussed above. Here we have introduced a cutoff function $e^{-\Lambda^2 Q'^2}$ to assure that the bound ϕ^0 - N system can be formed by the van der Waals potential mainly in the region that the relative motion between ϕ^0 and N is slow.

Neglecting the recoil energy of the final nucleus, the differential cross section of $A_i(\gamma, d)A_f$ can be calculated from the reaction amplitude defined above:

$$\frac{d\sigma}{dp_d d\Omega_d} \sim (2\pi)^4 p_d^2 E_N(p) p \int d\Omega_p |T_{fi}(p_d p; q, E)|^2, \quad (5)$$

where p is evaluated from energy conservation $q + Am_N = E_N(p) + E_d(p_d) + (A-2)m_N$ and the binding energy is neglected.

We have applied the above formula to calculate the photo-production of a ϕ - N bound state d from ^{12}C . The oscillator wave function parameter is chosen to be $b = 1.64$ fm. Figure 2 shows the calculated total cross section as a function of the photon energy and the cutoff parameter, Λ . For a given Λ value, the total cross section peaked around a photon energy of 1450 MeV, below the free production threshold of 1570 MeV. This peaking of the cross section below the threshold

is expected because of the enhancement of the van der Waals attractive force when the relative velocity between the intermediate ϕ and nucleons in the residual nuclear system is smallest. The cross section drops as the photon energy increases and reach 0.008 nb at $E_\gamma = 1800$ MeV. At a photon energy $E_\gamma = 1450$ MeV, the calculated total cross section is found to be $\sigma^{tot} = 1.4$ nb for a rather large cutoff $\Lambda = 3$ fm. Thus the production of the ϕ^0 - N is only accessible at energies below and near threshold.

Based on the total cross section calculated above, the search for the ϕ - N bound state is feasible experimentally by the triple coincidence detection of proton, K^+ , and K^- as described previously. Using a large acceptance detector system and a luminosity of $10^{35}/\text{cm}^2/\text{s}$ from an untagged photon beam at Jefferson Laboratory, the triple coincidence event from the ϕ - N bound state decay is estimated to be about 180/h at a subthreshold kinematics with an incident photon energy of 1450 MeV. An average flight path of 2 m for kaon detection, and realistic detector efficiencies were used in the above rate estimation.

In the case of the J/ψ -nucleon scattering, Brodsky and Miller [10] conclude that the gluonic van der Waals interaction dominates the scattering. The hadronic corrections to gluon exchange which are generated by $\rho\pi$ and $D\bar{D}$ intermediate states of the J/ψ are shown to be negligible. For the ϕ -nucleon system, the ‘‘intrinsic strangeness’’ in the

nucleon may complicate the simple picture of gluonic van der Waals interaction being the dominating interaction because of the possible strange quark exchange contribution. Thus, the experimental search for the ϕ - N bound state will not only help to unveil the nature of the QCD van der Waals force, but may also help to probe the strangeness content of the nucleon.

In conclusion, we found that the QCD van der Waals attractive force is strong enough to form a bound ϕ - N state inside the nucleus. Experimentally, it is possible to search for such a bound state using the ϕ meson below threshold quasifree photoproduction kinematics. Using a simple model, we calculated the rate for such subthreshold quasifree production process using a realistic Jefferson Laboratory luminosity and a large acceptance detection system. We conclude that such an experiment is feasible.

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