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Search for the ϕ-N bound state from ϕ meson subthreshold production

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The subthreshold photoproduction of ϕ mesons from heavy nuclear targets has been suggested as a candidate to search for the ϕ-N bound state, a quantum chromodynamics molecular state. In this Brief Report, we present detailed Monte Carlo studies to demonstrate the feasibility of this technique. Further, we show that proton-induced subthreshold production of ϕ meson from heavy nuclear targets is also suitable for such a search.

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Brodsky, Schmidt, and de Téramond [1] suggested that the quantum chromodynamics (QCD) van der Waals interaction, mediated by multigluon exchanges, is dominant when the two interacting color singlet hadrons have no common quarks. Luke, Manohar, and Savage [2] predicted that the QCD van der Waals interaction is enhanced at low velocity. This finding supports the prediction that a nuclear-bound quarkonium can be produced in charm production reactions at threshold. Brodsky, Schmidt, and de Téramond [1] investigated the nuclear-bound quarkonium state using 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 [3]. Using a variational wave function $\Psi(r) = (\gamma^3/\pi)^{1/2}e^{-\gamma r}$, they predicted bound states of η_c with ^{3}He and heavier nuclei. This prediction was later confirmed by Wasson [4] 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 because the ϕ meson is almost a pure $s\bar{s}$ state. Using the variational method and following Ref. [1] to assume $V_{(s\bar{s}),N} = -\alpha e^{-\mu r}/r$, Gao, Lee, and Marinov [5] found 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. Their results should be compared with $\alpha = 0.6$ and $\mu = 0.6$ GeV determined in [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 $s\bar{s}$. Because the radius of the ϕ meson is 0.4 fm [6], 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.

Recently, the ϕ-N bound state has been studied by Huang, Zhang, and Yu [7] using a chiral SU(3) quark model and the extended chiral SU(3) quark model solving the resonating group method (RGM) equation. The model parameters used by the authors in this work provided good description of baryon bound states, deuteron binding energy, and NN scattering phases shifts in their previous work [8,9]. A ϕ-N quasi-bound state with several MeV of binding energy was predicted by the aforementioned extended chiral quark model plus channel coupling effect.

Such a ϕ-N bound state could be formed [5] inside a nucleus at the quasi-free subthreshold photoproduction kinematics where the attractive force is expected to be enhanced. Recently, subthreshold ϕ-meson photoproduction has been observed [10] for the first time from a deuterium target at Jefferson Lab. 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 from subthreshold production of ϕ meson from heavy nuclear targets. To identify clearly the signal of a ϕ-N bound state, one needs to understand the background contributions to the pK^+K^- final state carefully. The dominant background contributions to the signal of interest are the quasi-free subthreshold production of ϕ meson from a bound proton and the subsequent decay of ϕ into K^+ K^- without the formation of a ϕ-N bound state, and the direct production of K^+ K^- from a bound proton inside the nucleus. Recently, we carried out a detailed Monte Carlo simulation of these processes. The Monte Carlo study shows that cuts on the momentum correlation between proton and $K^\pm$ and on the invariant mass of the K^+, K^- and proton system can clearly separate the signal of the decay of a ϕ-N bound state from the backgrounds. Therefore, one can identify a bound ϕ-N state experimentally using the aforementioned triple coincidence experimental technique. In this Brief Report, we present our results from the Monte Carlo studies.

The kinematics for all three channels considered in the Monte Carlo study for the detection of a ϕ-N bound state, using ^{12}C, ^{56}Fe, ^{63}Cu, and ^{197}Au target nuclei and the CLAS detector [11] at Jefferson Lab, follow a set of common parameters and assumptions. First, the energy of the photons in the subthreshold region is distributed uniformly from 1.65 to 1.75 GeV. This subthreshold energy range is roughly 80–180 MeV higher than that of a simulation that does not account for the geometry imposed by the CLAS detector for the triple coincidence detection of proton, K^+, K^-. The target nuclei are assumed to be initially at rest in the laboratory frame. For each event, the Fermi momentum and the missing energy for the bound proton are weighted by the nuclear spectral function. The nuclear spectral functions for the ^{12}C, ^{56}Fe, ^{63}Cu, and ^{197}Au nuclei are from Ref. [12]. A Breit-Wigner distribution with a mean value of 1.019413 GeV/c^2 and a width 0.00443 GeV/c^2 is used to model the mass of the ϕ meson that is produced. Furthermore, the ϕ mass for each event is bound between 0.819413 to 1.219413 GeV/c^2 to avoid unphysical masses.

Furthermore, the CLAS detector is modeled by applying cutoffs to the zenith laboratory angles that can be detected for the final state of each channel. From an analysis of the CLAS g10 data for the final state of pK^+K^- from ϕ-meson photoproduction [13], the minimum zenith laboratory angles for K^+ and K^- are 5° and 20°, respectively. Additionally, the resolution of the detector is incorporated into the simulation by weighing events using a Gaussian type distribution following the procedure developed for the Jefferson Lab Hall C proposal on electroproduction of ϕ using Hall C SOS and HKS magnets employing the missing mass technique [14]. Realistic numbers for the CLAS detector resolutions are used in our simulation.

The first channel considered is the subthreshold ϕ meson production from a bound proton with the subsequent decay of ϕ into K^+K^- without the formation of a ϕ-N bound state. The events simulated are weighted by the mass of the ϕ meson, and the Fermi momentum and missing energy of the bound proton. Before computing the kinematics of γ + "p" $\rightarrow$ $p + \phi$, the energies of γ and "p" are checked to ensure they are sufficient to produce a ϕ meson; events with insufficient energy are discarded. Given that no bound state is formed, the kinematics of the ϕ meson decaying into K^+K^- are calculated. At this point in the simulation, events for which the zenith laboratory angle of K^+ or K^- below the CLAS detector cut-offs are removed. Before simulating the detector's resolution, the calculations performed are tested in two ways: reconstructing the mass of the ϕ meson from the energy and linear momentum of the pK^+K^- final state; and reconstructing Fermi momentum of the bound proton from the four-vector of the initial and final state particles. Finally, the detector resolution is simulated for the pK^+K^- final state.

In the case of the second background channel, the direct production of K^+K^- from a bound proton, the simulation's structure is essentially the same as the structure of the first channel considered. An important distinction for the second background channel is the direct production of the three-particle final state from the γ + "p" $\rightarrow$ $p + K^+ + K^-$ process, which is simulated by the following sequence of steps. For computational purposes, it is assumed that the direct production of K^+K^- can be simulated by γ + "p"$\rightarrow (AB) + C \rightarrow A + B + C$, where A, B, and C are combinations of proton, K^+, and K^-. The intermediate step of the simulation, $(AB) + C$, has no physical significance and merely serves as a tool for kinematic calculations. Given that $K^\pm$ are assumed to be kinematically indistinguishable in the simulation, there are only three kinematically distinct combinations, each of which is assumed to have an equal probability of occurring. Thus, each event is weighted by the uniform distribution of the different sequence of the same three-particle final state. Similarly to the first channel, the Fermi momentum of the bound proton is reconstructed to ensure all calculations are carried out correctly.

The last channel studied is exactly the same as the first, with the exception of the formation of a ϕ-N bound state in the nuclear medium. For the purposes of the simulation and the detection setup, the nucleon to which the ϕ meson binds is modeled as a proton. It is assumed that QCD van der Waals forces lead to the formation of a ϕ-N between the photo-produced ϕ meson and a bound proton if the ϕ particle has a linear momentum less than 400 MeV/c. The momentum of the bound proton is assumed to be the same as that of the ϕ when considering the formation of the ϕ-N state. The ϕ-N exotic state is assumed to have a binding energy of 2.5 MeV [5]. When considering the decay of ϕ-N into the pK^+K^- final state, the kinematic methodology used for the direct production of K^+K^- from bound proton is reused. Once again, the simulation is checked by reconstructing the mass of the ϕ meson and the Fermi momentum of the bound proton. Figure 1 shows the invariant mass distribution of the p, K^+, K^- system for all these three channels, and the

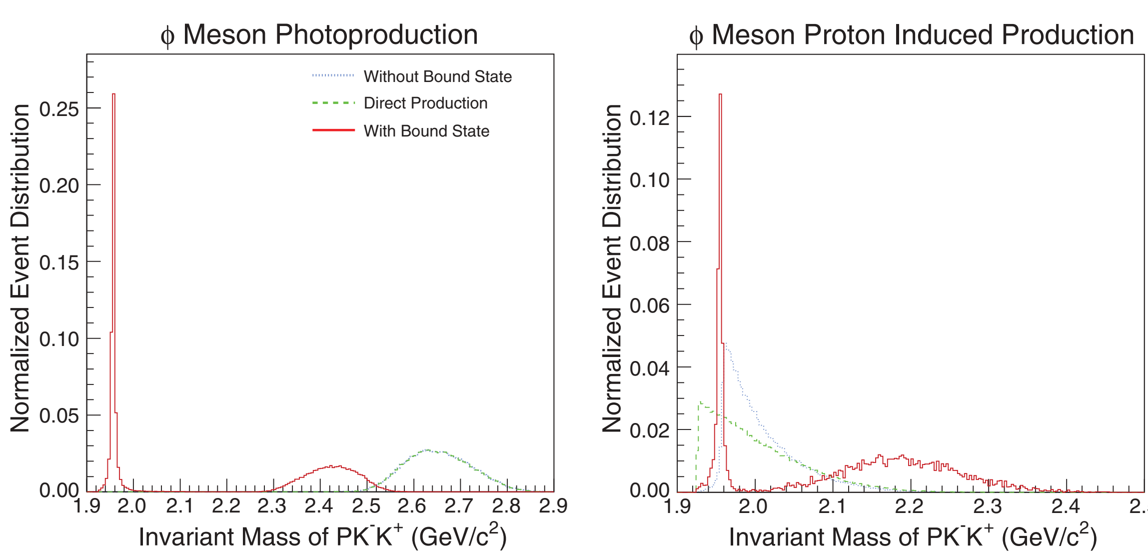

FIG. 1. (Color online) Monte Carlo simulation of the invariant mass distribution of the proton, K^-, and K^+ system for the following three processes from a copper target: ϕ-N bound state (solid); quasi-free subthreshold ϕ production without the formation of a bound state (dotted); direct production of the pK^+K^- process (dashed). The left and the right panels show the photo- and proton-induced ϕ subthreshold production, respectively.

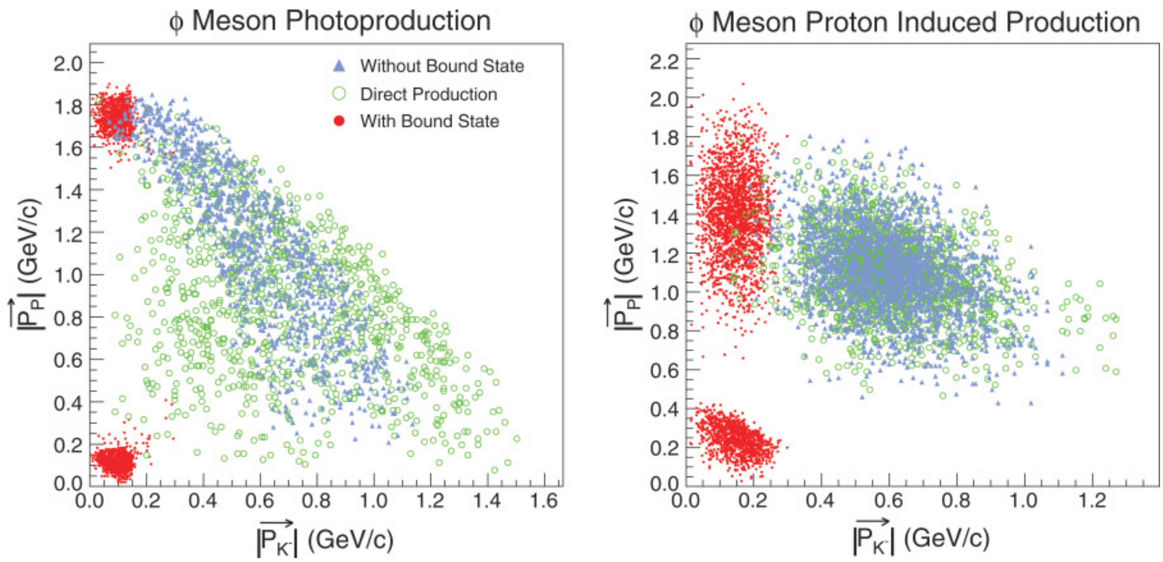

FIG. 2. (Color online) Monte Carlo simulation of the proton momentum versus K^- momentum for the three processes from a copper target described in the text. To improve the visibility of the figure, we plot 1000 successful events for each channel only, whereas our overall results are based on analyzing 45,000 successful events for each channel.

histogram for each of the channels has been normalized to unity. In the case of the ϕ-N bound state, the prominant peak corresponds to the proton from the decay of the ϕ-N bound state is detected with the second bump corresponding to the recoil proton(s) from the subthreshold ϕ production process being detected.

The search of the presence of a ϕ-N bound state is based on the triple coincidence detection of the kinematically correlated K^+, K^-, and the proton in the final state. Such a signature is clearly identified when comparing the absolute value of the linear momentum of the $K^\pm$ and the scattered protons. We are able to segregate the events corresponding to the channel with the ϕ-N bound state by applying one graphical cut, and another cut on the invariant mass of the pK^+K^- final state. The graphical cut involves removing all events for which the square sum of the linear momentum of K^- or K^+ and the proton is greater than $(0.300\ \text{GeV}/c)^2$. The second cut consists of only considering events where the invariant mass of the pK^+K^- final state falls in the region of $1.955 \pm 0.010\ \text{GeV}/c^2$. The results from the simulation using ^{12}C, ^{56}Fe, ^{63}Cu, and ^{197}Au target nuclei have demonstrated that the channel for ϕ-N is completely segregated from the two other background channels. Only about 13% of events for the channel containing the ϕ-N bound state are eliminated due to these two cuts with no additional cuts from the detectors. An example is shown for the case of the Copper nucleus before (Fig. 2) and after (Fig. 3) the momentum and invariant mass cuts discussed in the text.

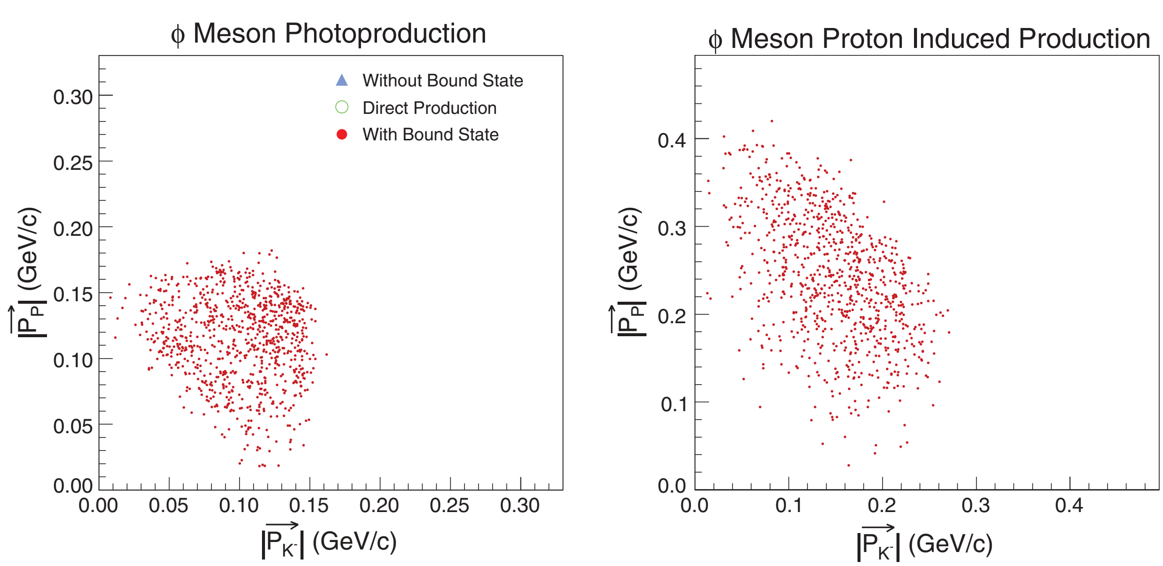

FIG. 3. (Color online) Same as Fig. 2 except for the momentum and invariant mass cuts applied (see text).

To increase the feasibility of experimental detection of a ϕ-N bound state a Monte Carlos analysis similar to that of subthreshold ϕ meson photoproduction is carried out for subthreshold proton-induced ϕ production. The overall conclusions from the proton-induced production are the same as those for photoproduction, namely that the events containing ϕ-N bound states can be completely separated from background channels. The three channels considered for the proton-induced ϕ production are equivalent to those considered in photoproduction, with the distinction of the different incident beam. Once again the simulation is conducted in the subthreshold region, to minimize the momentum mismatch between the produced ϕ meson and the bound nucleons and to obtain a clear kinematic signature for the presences of ϕ-N bound state when comparing the final state momentum value of the final state particles. The incident proton's total energy for the simulated events is weighed by a uniform distribution in the subthreshold range of 3.30–3.50 GeV, where the threshold energy is 3.53 GeV.

Even though the analysis for proton-induced production is similar to that of photoproduction; there are some important kinematic distinctions that arise from having to consider an additional proton during the various stages of the simulation. When simulating the channels where a ϕ meson is produced from a bound proton the methodology used for the direct production of K^+K^- in photoproduction is reused, noting that the different kinematic combinations now involve two protons and one ϕ meson. For the channel corresponding to the direct production of K^+K^- we need to consider the four-particle final state: $p+$ "p" $= p + p + K^+ + K^-$. This process is simulated by $p+$ "p" $\rightarrow (AB) + (CD) \rightarrow A + B + C + D$, where A, B, C, and D are combinations of p, p, K^+, and K^-. Following the assumption that $K^\pm$ are kinematically indistinguishable we observed only two dynamically different sequences, which are attributed an equal probability of occurring. Each event is weighted by uniform distribution of the two different sequences. Another important difference of the proton induced ϕ production when compared to photoproduction is that for the channel assuming the presence of a ϕ-N bound state the condition for such a bound state occurring is that the linear momentum of the ϕ meson is less 500 MeV/c (as opposed to the 400 MeV/c used for photoproduction). This increase of the ϕ-meson upper momentum limit is necessary due to the overall higher momentum distribution of the ϕ meson produced. Although high-momentum protons inside nuclei are suppressed, one still expects more ϕ-N bound state events from proton-induced reaction due to the nature of the strong interaction. Such an experiment can be carried out in the future at the CSR facility in Lanzhou, China, where one can design a new detection system particularly suitable for this search.

The presence of a ϕ-N bound state is observed when comparing the final state momentum of the protons and kaons using two cuts to isolate the channel with the ϕ-N bound state in the proton induced production. The first cut removes all the events for which the squared sum of the final state momentum of K^- or K^+ and proton is greater than $(0.450\ \mathrm{GeV}/c)^2$. The second cut is the same as that for the photoproduction case that is on the invariant mass of the final state pK^-K^+. These two cuts yield a clear and uncontaminated kinematic signature for the presence of a ϕ-N bound state. The percentage on events from the channel containing the ϕ-N bound state eliminated due to these two kinematic cuts is about 11% with no additional cuts from the detectors.

In the two cases presented in this work, the kinematic cuts described are able to separate the signal cleanly from the main physics backgrounds, therefore it is not necessary to carry out the simulations with cross-section weighting. To carry out such a search at Jefferson Lab, the feasibility of using the CLAS BONUS- [15] type recoil detector for detecting low-momentum charged particles will be studied in the near future.

In summary, we carried out detailed Monte Carlo studies of subthreshold ϕ-meson production from photo- and proton-induced reactions to demonstrate the feasibility of experimental search for ϕ-N bound state from heavy nuclear targets at Jefferson Lab in the United States and the CSR facility in Lanzhou, China. S.L. thanks D. Dutta for helpful discussions. This work is supported by the U.S. Department of Energy under contract number DE-FG02-03ER41231.

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