Search for $\phi$-$N$ Bound State in Jefferson Lab Hall B

Haiyan Gao (高海燕)
Duke University

QCD: still unsolved in non-perturbative region

- 2004 Nobel prize for “asymptotic freedom”
- non-perturbative regime QCD ??????
- One of the top 10 challenges for physics!
Why care for QCD exotics?

QCD does not eliminate the existence of hadrons beyond simple \((q \overline{q})\) or \((qqq)\) as a color-singlet system.

- How confinement manifests itself at large distances?
- What leads to the chiral symmetry spontaneous breaking?
- What are the proper effective degrees of freedom for a hadron?
- ... ...

Qiang Zhao
**Brief Recap on van der Waals Forces**

1873: To explain deviations from ideal gas behavior, van der Waals proposed a modification to the gas law:

\[
\left( P + \frac{a}{V^2}\right)(V - b) = RT
\]

Reasoned out:
• Molecules have finite volume (accounted by “b”)
• Attractive forces between the molecules (accounted by “a”)

The relation predicted gas behavior across a larger pressure range.

The attractive intermolecular forces between gas molecules is now known as “van der Waals forces”
van der Waals Forces

The three components that constitute van der Waals Forces

<table>
<thead>
<tr>
<th>Interaction Component</th>
<th>Origin of Interactions</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Keesom</td>
<td>Dipole-dipole</td>
<td>$w(r) = -\frac{u_1^2 u_2^2}{3(4\pi\varepsilon_0 \varepsilon_r)^2 k_B T} \frac{1}{r^6}$</td>
</tr>
<tr>
<td>Debye</td>
<td>Dipole – induced dipole</td>
<td>$w(r) = -\frac{u^2 \alpha_o}{(4\pi\varepsilon_0 \varepsilon_r)^2} \frac{1}{r^6}$</td>
</tr>
<tr>
<td>London (Dispersion)</td>
<td>Induced Dipole – Induced Dipole</td>
<td>$w(r) = -\frac{3}{2} \frac{\alpha_{o1} \alpha_{o2}}{(4\pi\varepsilon_0)^2} \frac{I_1 I_2}{(I_1 + I_2)} \frac{1}{r^6}$</td>
</tr>
</tbody>
</table>

The London component is the most dominant. $n = 6$ indicates van der Waals forces are short range.
van der Waals interaction between two CH₄ molecules

Unsymmetrical electron density creates a temporary dipole.

The effect of polarizability on intermolecular interactions

small, less polarizable atoms
smaller force of attraction

large polarizable atoms
stronger force of attraction

Figure 3.2 Surface area and van der Waals forces

long, cylindrical molecule
Example: CH₃CH₂CH₂CH₂CH₃ pentane

larger surface area
stronger van der Waals interactions

smaller surface area
weaker van der Waals interactions

Example:
\[
\text{CH}_3\text{CH}_3 \\
\text{C} \text{C(CH}_3\text{)}_2\text{CH}_3 \text{ neopentane}
\]
Question: are there any QCD molecular state?

Answer: maybe
Discovery of the X(3872)

- In 2003, Belle discovered a new signal in $B^+ \rightarrow X K^+$, $X \rightarrow J/\psi \pi^+ \pi^-$
- Narrow ($\Gamma < 2.3\text{MeV}$) particle with mass $m(X) = 3871.2 \pm 0.6 \text{MeV}/c^2$

Confirmed by CDF, D0 and BaBar

**X(3872) Interpretation**

- **X(3872) is puzzling**
  - Similar to charmonium, i.e.: narrow state decaying to $J/\psi \pi^+\pi^-$
  - However, above DD threshold expect to be wide and $X \rightarrow$ DD dominant
  - Quantum numbers established: $1^{++}$
  - It does not fit into the charmonium model

- **Note:**
  $$m(X) \approx m(D) + m(D^*_{0})$$

- **Leading contender:** a bound state of two D mesons
  - i.e.: a $D^0D^{*0}$ molecule
  - Supported by predictions of mass, decay modes, $J^{PC}$, branching fractions

- **Other exotic predictions:**
  - “Tetraquark” 4-quark bound state
  - “Glueball” gluon bound state, charmonium-gluon hybrid
Charmonium Spectrum Revisited

M [GeV]

New cc
New ??
Observed
Predicted
**Belle results Z+(4430)**

\[ \mathcal{B} \rightarrow \mathcal{K} \pi^{\pm} \psi' \]

\[ M = (4.433 \pm 0.004\text{(stat)} \pm 0.001\text{(syst)}) \text{ GeV} \]

\[ \Gamma = (0.044^{+0.017}_{-0.013}\text{(stat)}^{+0.030}_{-0.011}\text{(syst)}) \text{ GeV} \]

Slide: Qiang Zhao  
First charmonium with isospin I=1!

Tetraquark state? (Ebert et al; Rosner; Maiani et al; Lee)
Molecular state of D* D1? (Bugg; Liu et al)
Subthreshold effects due to D* D1? (Bugg; Chao et al)
Baryonium? (Qiao)

......

Why not seen in J/ψ π?
Can it couple to ρηc?
Where are its flavor partners?

......

Strong coupling for Z(4430)→ψ′π
Can meson-baryon form a molecule?
Nuclear-Bound Quarkonium

- **Proton-proton scattering**: intriguing behavior in spin correlation, nuclear transparency
- **QCD van der Walls interaction**, mediated by *multi-gluon exchanges*, is dominant when the two interacting color singlet hadrons have **no common quarks**. **QCD analog** of the attractive QED van der Waals potential
- No Pauli blocking, effective quarkonium-nuclear interaction will not have a short-range repulsion
- Suggested a bound state of charm quarkonium to $^3$He nucleus: $\eta_c^{-3}$He by studying proton capture on deuteron
- Binding energy $\sim 20$ MeV, width $\sim$ tens of keV.
$27\text{Al}(p,2p)$


$P + p \rightarrow \Lambda_c Dp$

**φ-N Bound State (suggested by Isgur)?**

  - The interaction is expected to be enhanced by
    \((m_c/m_s)^3\), following Brodsky et al. PRL 64, 1011 (1990)
  - Varitional method with
    \[ V_{(q\bar{q})A} = -\frac{\alpha e^{-\mu r}}{r}, \quad \alpha = 1.25, \quad \mu = 0.6 \]
  - **Binding energy ~ 2 MeV**
  - \(\phi-N\) can be formed inside heavy nuclei through quasi-free \(\phi\) photoproduction.
**φ-N bound state in chiral quark model**

- Chiral SU(3) quark model and the extended chiral SU(3) quark model solving the RGM equation
- Model parameters from previous work give good descriptions of
  - Baryon ground states
  - Deuteron binding energy
  - NN scattering phase shifts
- Extended chiral quark model plus channel coupling effect → φ-N quasi-bound state with several MeV of binding energy
Creation of $\phi$-N Bound State in Heavy Nuclei

- “Sub-threshold” generated $\phi$ is slow enough to bound with nucleon
- $\sigma^{\text{tot}} \sim 1.4 \text{ nb}$ on $^{12}\text{C}$ nucleus.

$\phi$ production threshold on Hydrogen target

Possible Way to Detect $\phi$-N

- “Sub-threshold” $\phi$ production in nuclei.
  - Can use real photon, electron or proton beam.
  - Need to tag energy of real/virtual photon.

- Detect all final states of $\phi$-N bound state decay to reconstruct its invariant mass.
  - $\phi - N \rightarrow p_2' + K^+ + K^-$: triple coincidence
  - Other decay channels (see later)

- Jefferson Lab Hall B is a possible place to search for such particle:
  - Large acceptance detector and tagged photon beam.
  - Good particle identification.
Background Channels

- Four major background channels
  - Direct production:
    \[ \gamma + p_1 \rightarrow p_1' + K^+ + K^- \]
  - No Bound State:
    \[ \gamma + p_1 \rightarrow p_1' + \phi \rightarrow p_1' + K^+ + K^- \]
  - \( \Lambda(1520) \) Production:
    \[ \gamma + p_1 \rightarrow \Lambda(1520) + K^+ \rightarrow p_1' + K^- + K^+ \]
  - \( a_0/f_0 \) production
    \[ \gamma + p_1 \rightarrow p_1' + a_0/f_0 \rightarrow p_1' + K^+ + K^- \]
- Bound state formed but \( K^+ K \) coincide with the recoil proton \( p_1' \).
Phase Space Simulation

Done by S. Liska and Y. Qiang.
On four nuclear targets: $^{12}\text{C}$, $^{56}\text{Fe}$, $^{63}\text{Cu}$ and $^{197}\text{Au}$.
Fermi motion and missing energy distributions were taken into account in the simulation of quasi-free process.
The following results were from $^{63}\text{Cu}$ target with photon energy $E_\gamma = 1.35 \sim 1.55 \text{ GeV}$
Preliminary study with cross section weighting done by S. Liska (Duke senior thesis, 2008)
Invariant Mass of p K^+ K^- 

- $\phi$-$N$ bound state (5 MeV width assumed) mixed with other channels.
- $\phi$-$N$ bound state can be clearly identified (5 MeV width assumed).
Momentum Distributions

- $\phi$-$N$ bound state can be clearly identified (50 MeV width assumed).
Angles of Final States

- All particles are produced forward while the final states of $\phi$-$N$ bound state have the largest angles.
Summary of $\phi$-N Final States

$\phi$ - $N \rightarrow p_2' + K^+ + K^-$

- $p_2'$: 200 ~ 500 MeV/c 10° ~ 40°
- $K^+$: 100 ~ 300 MeV/c 13° ~ 52°
- $K^-$: 100 ~ 300 MeV/c 13° ~ 52°
Evidence of $\phi$ Production from Fermi Motion

- X. Qian et al. CLAS g10 data, $E_\gamma = 1.65$–$1.75$ GeV (currently reviewed by CLAS ad hoc committee)
Evidence of $\phi$ Production from Fermi Motion

$\gamma(d, p K^+ K^-) n \quad \gamma(p, p' K^+ K^-)$

- X. Qian et al. CLAS g10 data, $E\gamma = 1.65\sim1.75$ GeV (currently reviewed by CLAS ad hoc committee)
Study on BoNuS Detector

- Radial Time Projection Chamber (RTPC) using GEM foils.
- Active drifting volume: L=20 cm, R=3 cm.
- Longitudinal field is generated by Møller solenoid (2~7 T).
- Can be used to detected low momentum charged particles (< 250 MeV/c).
- GEANT4 simulation code by J. Zhang.
BoNuS uses energy loss $dE/dX$ and momentum reconstructed from measured curvature to identify charged particles.
Only low momentum (<200MeV/c) could be reconstructed correctly.
Number of Hits

More than 3 hits are required to define a track:

- Proton
- Kaon
- Pion
The BoNuS RTPC can identify charged particles with momentum below 200 MeV/c.

The use of CLAS seems to be necessary.
Other decay channels of phi-N?

- Two channels have larger phase spaces
  - Decay into Lambda and kaon:
    \[ \phi - N \rightarrow \Lambda^0 + K^+ \rightarrow p + \pi^- + K^+ \]
  - Decay into Sigma and kaon:
    \[ \phi - N \rightarrow \Sigma^0 + K^+ \rightarrow \Lambda^0 + \gamma + K^+ \rightarrow p + \pi^- + \gamma + K^+ \]

- Simulations carried for these two decay channels (see next slides)
Phase Space Simulation

- Performed by Y. Qiang.
- One nuclear target as a test case: $^{63}$Cu.
- Fermi motion and missing energy distributions were taken into account in the simulation of quasi-free process.
- Simulations also taken into account two phi-N state widths: 5 MeV and 50 MeV
- The following results were from $^{63}$Cu target with photon energy $E_\gamma = 1.35 \sim 1.55$ GeV.
- $\phi$-$N$ bound state with 5 MeV width, separation possible by detecting the original recoiling proton and the decaying kaon and pion, **can not reconstruct the invariant mass of the bound state**

- Development of cuts needed to separate the signal from the background (Poy Torngern, Duke undergraduate)
- \( \phi-N \) bound state with 50 MeV width, separation possible by detecting the original recoiling proton and the decaying kaon and pion, can not reconstruct the invariant mass of the bound state

- Development of cuts needed to separate the signal from the background
Upper left panel:
Blue: direct Lambda
Green: direct Sigma
Red: bound Lambda decay
Light blue: bound Sigma decay

Lower panel:
Left black: direct Lambda
Right black: direct Sigma
Color: bound Lambda decay
Upper panel:
Left black: direct Lambda
Right black: direct Sigma
color: bound sigma decay

Lower panel: color code
Switched
Sigma decay has better Separation, not able to
Reconstruct the mass of
The bound state
I. Triple Coincidence of $K^+K^\prime N$

$$\gamma p_1 p_2 \rightarrow \phi p'_1 p_2 \rightarrow (\phi p'_2) p'_1 \rightarrow K^+ K^- p'_1 p'_2$$

Identification of the $\phi$-N bound state from other background channels was achieved by investigating their kinematics correlations through a phase space simulation.


Easier experimental configuration: $\phi$-N $\rightarrow$ $\phi p$

Need a clear separation of bound state (red) channel from the backgrounds

Need a clear separation of bound state (red) channel from the backgrounds

2D Momentum Separation between proton and the kaon system
II. $K\Lambda$ and $K\Sigma$ decay

\[ \phi p \rightarrow \Lambda(1116)K^+ \rightarrow p'\pi^-K^+ \]

\[ \phi p \rightarrow \Sigma^0(1193)K^+ \rightarrow \Lambda\gamma K^+ \rightarrow p'\pi^-\gamma K^+ \]

Desired bound states are $\phi$-N to $\Lambda^0$ (red) and $\phi$-N to $\Sigma^0$ (blue)

Best momentum separation suggests possibility of identifying bound state channels (red and blue)

Any kinematic relationship to identify such bound state channels?
Absolute sum of momentum

$$\left| \vec{P}_p + \vec{P}_{K^+} + \vec{P}_{\pi^-} \right|$$

0.5% resolution

Apply a cut

$$\left| \vec{P}_p + \vec{P}_{K^+} + \vec{P}_{\pi^-} \right| < 1 \text{ GeV/c}$$
Longitudinal Missing Momentum
\[ E_{y} - \left( | \vec{P}_{p_{z}} | + | \vec{P}_{K_{z}}^{+} | + | \vec{P}_{\pi_{z}}^{-} | \right) \]

vs

Total perpendicular momentum
\[ \left| (\vec{P}_{p} + \vec{P}_{K_{z}}^{+} + \vec{P}_{\pi_{z}}^{-})_{\perp} \right| \]

Apply a cut

Coordinate system
\[ E_{y} - \left( | \vec{P}_{p_{z}} | + | \vec{P}_{K_{z}}^{+} | + | \vec{P}_{\pi_{z}}^{-} | \right) > 0.48 \; \text{GeV/c} \]

and
\[ \left| (\vec{P}_{p} + \vec{P}_{K_{z}}^{+} + \vec{P}_{\pi_{z}}^{-})_{\perp} \right| < 0.45 \; \text{GeV/c} \]
Identification of the $\phi$-N bound state channels in $K\Lambda$ and $K\Sigma$ decay was achieved by applying three cuts. The first cut is to remove all events of absolute sum of the final product's momenta that is greater than 1 GeV/c. The second cut is accepting all events of longitudinal missing momentum of the final product that is greater than 0.48 GeV/c. The last cut is eliminating all events of total perpendicular momentum that is greater than 0.45 GeV/c. The final result, in the invariant mass distribution, demonstrates a clear separation of the bound state as shown.
Experimental strategy

- Detect all three charged particle final states with two positively charged particles and one negative charged particle including proton, kaons and pions.
- More simulations including cross sections necessary.
- Particle identification and large acceptance are crucial for the search.
Recent observations of similar charmed molecular states at electron-positron colliders indicate that this may be a very interesting experiment. It has long been thought that the scalar mesons, \( a_0, f_0(980) \), may well be molecular in nature with hidden strangeness. Clear observations in recent years of several possibly molecular states with hidden charm have strengthened this idea. It is then natural to study whether baryons with such hidden strangeness exist and serve to motivate this proposal.

However, one possible concern is the effect of the interaction of such a molecular state with other nucleons in a nucleus. It would be very useful if the theory could be further developed before a submission of a full proposal to a future PAC.
Theoretical issues and help needed

- Final state interaction of the bound state with other nucleons inside the nucleus (PAC comment)
- Theoretical investigation of the width and the decay branching ratio of the bound state
- More theoretical study of the production cross-section
- Can one observe such a state on the lattice (private communications with K.F. Liu)?
Summary

- The search of $\phi$-$N$ bound state (QCD molecular state) is important and exciting

- $\phi$-$N$ bound state predicted to have moderate cross section in sub-threshold $\phi$ photo-production

- Potential decay channels of KK, KLambda, and KSigma investigated, promising for identifying the bound state

- Jefferson Lab Hall B - a good place to carry out the search
  - Our study on the BoNuS RTPC has been done
  - Study on CLAS detector is still underway

- CLAS12 will be better

Supported by U.S. DOE under contract number DE-FG02-03ER41231

Acknowledgement: Y. Qiang, S. Liska, X. Qian, Poy Torngern, S. Kuhn, J. Zhang, Thia Keppel, M. Strikman, K.F. Liu, Q. Zhao, and others