Probing $\phi$ Mesons in Deuteron Break-up Reactions

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February 20, 2013
Hadron-nucleon interactions, such as heavy quarkonium scattering, can be difficult to experimentally probe.

The reaction $^2H(\gamma, hp)n$ may prove a fruitful means of probing these interactions.

The trick lies in analyzing the effects of final state interactions—deuteron electrodisintegration serves as an example.
Deuteron Electrodisintegration

- Deuteron electrodisintegration, i.e. $^2H(e, e'p)n$ was experimentally studied by Egiyan et al. (PRL 98, 262502), and subsequently by Boeglin et al. (PRL 107, 262501).
- Observing a fast proton ($p_p > 1 \text{ GeV}$) ensures that the proton was struck, and ensures the eikonal regime.
- For particular values of $p_n$, the differential cross-section is plotted against $\theta_{nq}$.
- The results show valleys and peaks around $\theta_{nq} = 70^\circ$ depending on $p_n$. 
Egiyan et al. (PRL 98, 262502)

- Peak at $\theta_{nq} \approx 70^\circ$ for $p_n \in (400, 600)$ MeV.
- Valley at $\theta_{nq} \approx 70^\circ$ for $p_n \in (200, 300)$ MeV.
- Dashed, dash-dotted, and solid are respectively PWIA, PWIA+FSI, and PWIA+FSI+MEC+$N\Delta$.
- Left and right columns are respectively $Q^2 \approx 2$ GeV$^2$ and $Q^2 \approx 3$ GeV$^2$. 
Boeglin et al. (PRL 107, 262501)

- Peak at $\theta_{nq} \approx 75^\circ$ for $p_n = 400, 500$ MeV.
- Valley for $p_n = 200, 300$ MeV.
- Purple line is theoretical prediction by Sargsian (PRC 82, 014612), black (dash-dotted) and green by Laget (PLB 609, 49) with and without MEC and $N\Delta$, respectively.
- $Q^2 = 3.5$ GeV$^2$. 

![Graph showing data and theoretical predictions for $R = \sigma_{\text{exp}}/\sigma_{\text{FWIA}}$ versus $\theta_{nq}$]
These results are due to final state interactions (FSI’s).

In Feynman diagram language, the most relevant reactions are

(a) PWIA

\[
\begin{array}{c}
\gamma^* \rightarrow p \\
\downarrow d \rightarrow n
\end{array}
\]

(b) \(pn\) rescattering

\[
\begin{array}{c}
\gamma^* \rightarrow p \\
\downarrow d \rightarrow n
\end{array}
\]

The plane wave impulse approximation (PWIA) is just the product of the electron-proton scattering amplitude and the deuteron wave-function.

PWIA is corrected by a scattering of the proton off the spectator neutron.

I’ll neglect further corrections (MEC, \(N\Delta\), etc.).
Hadron Production

- What if a hadron is produced in photodisintegration? (Real photons.)
- There would be three particles in the final state—another FSI.

![Diagram](image)

(c) PWIA

(d) pn rescattering

(e) hn rescattering

- We will find a second rescattering peak.
ϕ Photoproduction

- As a particular example, look at $\phi(1020)$ as the hadron.
- $\phi$ photoproduction from the proton has been studied extensively, such as by Mibe et al. (PRL 95, 182001).
- The exact form of the $\phi N$ scattering amplitude is unknown, but vector meson dominance (VMD) seems to reproduce coherent $\phi$ production from the deuteron—cf. Mibe et al. (PRC 76, 052202)—and will serve as a proof of principle.
Kinematics and Definitions

- Momentum transfer for photoproduction is defined thus:
  \[ l = p_\gamma - p_\phi \]
  \[ t = l^2 \]

- Differential cross-section is plotted against \( \theta_{nl} \), illustrated by this graphic:

- The cross-section ratio is plotted instead of absolute cross-section.
  \[ R = \frac{\left( \frac{d^5 \sigma}{dp_\phi d\Omega_\phi d\Omega_p} \right)}{\left( \frac{d^5 \sigma_{\text{PWIA}}}{dp_\phi d\Omega_\phi d\Omega_p} \right)} \]
There is a distinct peak for each FSI!
Mibe et al. (PRC 76, 052202) point out—two models fit the data:

1. VMD with $\sigma_{\phi N} = 10$ mb

2. $\sigma_{\phi N} = 30$ mb, and $B = 10$ GeV

The 30 mb model was inspired by a result of $\sigma_{\phi N} = 35^{+17}_{-11}$ mb in nuclear media, found at SPring-8 by Ishikawa et al. (PLB 608, 215)
Alternative Model

\[ \sigma_{\phi N} = 30 \text{ mb and } B = 10 \text{ GeV}^{-2} \]
Alternative Model

There’s a clear difference between the models.
Double rescattering

The treatment would not be complete without double rescattering:

\[ \gamma \rightarrow h \rightarrow n \rightarrow p \]

\[ d \rightarrow h \rightarrow n \rightarrow p \]
Double rescattering

- The treatment would not be complete without double rescattering:

- This suppresses the rescattering peaks and valleys in the 30 mb model.
Double rescattering

- For VMD, the suppression is negligible.

\[ R \propto 10^0 \quad \text{for } \theta_{nl} (\text{deg}) \]

- This is because the double scattering amplitude is proportional to \( \sigma_{\phi N} \).
There’s still a clear difference between the models.
**Double rescattering**

- There’s still a clear difference between the models.

  ![Graph](image)

- Can the J-Lab data-mining group find evidence for this reaction and choose a preferred model?