Kaon Electroproduction on Few-Body Systems
Jefferson Lab Experiment E91-016

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presented at
HYP2003
October 17, 2003
Outline

- Motivation/history
- Experimental program
- Ln final state interaction
- S production off the neutron
- 3,4He data
- Parasitic analyses: w, $^{12}$C, $^{27}$Al
Once Upon a Time
(last millenium)

Dec. '89 & Mar '90: PAC4 deferes PR89-013
Nov. 1991: PAC5 approves E91-016
Jan '96: PAC10 gives E91-016 A- rating
E91-016 Goals

Electroproduction of $K^+$ on D, 3He, 4He

First survey of the $(e,e'K)$ reaction on complex nuclei

Choose light nuclear targets because of large cross sections for Kaon production; Measurements have good signal/background ratios; good yields with short runs.

Measure quasifree L and S production on D, $^{3,4}\text{He}$ at $E_e=3$ GeV, $E_{e'}=1-1.5$ GeV, $q=1.5-2$ GeV

Measurement of $K^+$ production on D, $^{3,4}\text{He}$ with high precision provides:
  a) <3% statistical error over most of the missing mass spectrum
  b) the 3HL and 4HL bound state yields with <3% errors
  c) experimental data for $K^+\text{-p}$ and mass dependence of various rates, backgrounds, etc.

$K^+$ production on D sensitive to L-N and S-N intercations; study L-N and S-N intercations in the cusp region

Very few data available, even for H; theoretical calculations by Cotanch, Donelly, and others

Measure hypernuclear bound state production on $^{3,4}\text{He}$

Tests reaction dynamics and wave functions

Possibility of observing: bound S hyper-nuclear states; di-baryons

Provides a solid basis for planning future studies; a comprehensive base for hyper-nuclear studies; measurements extendable to cover wide range of energies and angles
Predictions for $D(e,e'K^+)$
S.R. Cotanch and S.S. Hsiao, T.W. Donnelly and S.R. Cotanch
**Experimental Program**

Short Orbit Spectrometer, SOS  
kaon arm

High Momentum Spectrometer, HMS  
electron arm

### Targets: $^1$H, $^2$H, Carbon, Aluminum

**1996**

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>$(Q^2, W)$</th>
<th>$\theta_{K,lab}$ (°)</th>
<th>$(Q^2, W)$</th>
<th>$\theta_{K,lab}$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ebeam=3.245 GeV</td>
<td>$(0.50, 1.80)$</td>
<td>$(0.52, 1.76)$</td>
<td>$0.0, 4.3, 8.3, 13.3$</td>
<td>$(0.38, 1.90)$</td>
</tr>
<tr>
<td>Ebeam=2.245 GeV</td>
<td>$(0.50, 1.80)$</td>
<td>$(0.52, 1.76)$</td>
<td>$1$</td>
<td>$(0.38, 1.90)$</td>
</tr>
</tbody>
</table>

### Targets: $^1$H, $^2$H, $^3$He, $^4$He, Carbon, Aluminum

**1999**

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>$(Q^2, W)$</th>
<th>$\theta_{K,lab}$ (°)</th>
<th>$(Q^2, W)$</th>
<th>$\theta_{K,lab}$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ebeam=3.245 GeV</td>
<td>$(0.35, 1.91)$</td>
<td></td>
<td>$(0.0, 6.0, 12.0)$</td>
<td></td>
</tr>
</tbody>
</table>
**Particle Identification**

K+ PID:
- Coincidence time cuts separate 99.9 % real K⁺, π⁺, p
- Aerogel cuts reject 98 % π⁺
- b cuts reject 99 % p

e⁺ PID
- Cerenkov and calorimeter have ~ 99.8 % efficiency for electron
- PID
Missing Mass Analysis for \( p(e,e'K^+)X \)

\[
\begin{align*}
\vec{p}_e &\to \vec{p}_p = \vec{p}_e' \to \vec{p}_K \to \vec{p}_{miss} \\
0 \left( \begin{array}{l}
E_e \\
M_p
\end{array} \right) &\to \left( \begin{array}{l}
E_e' \\
E_K \\
E_{miss}
\end{array} \right)
\}
\end{align*}
\]

\[
m_{miss}^2 = E_{miss}^2 + p_{miss}^2
\]
H(e,eK) Monte Carlo: SIMC

- Generate $p_e$ and $\hat{p}_K$
- $m_Y$ determines $|p_K|$
- Use reasonable model for $ds/dW$
- Radiate event
- Transport through spectrometers
- Reconstruct
- Compare with data
- Iterate $ds/dW$ until data and MC agree
Simple Model for Hydrogen Data

\[ \frac{d\sigma}{d\Omega} = f(Q^2)g(W)h(t)i(\phi) \]
X-section parametrization

\[ f(Q^2) = \text{Constant} \] (5.2)

\[ g(W) = \frac{P_1 P_k^{CM}}{(W^2 - M_p^2)W} + \frac{P_2 W^2}{(P_3 W)^2 + (W^2 - P_4^2)^2} \] (5.3)

\[ h(t_{min} - t) = P_1 e^{P_2(t_{min} - t)} \] (5.4)

\[ i(\phi) = P_1 + P_2 \cos(\phi) + P_3 \cos(2\phi) \] (5.5)
Momentum Wavefunction (Bonn potential)
$^2\text{H}(e,e'K^+)$

d$(e,eK^+)YN$

- Quasifree Monte Carlo
- $d(e,eK^+)\Lambda^0n$
- $d(e,eK^+)\Sigma^0n$
- $d(e,eK^+)\Sigma^-p$
- $\Lambda^0n + \Sigma^0n + \Sigma^-p$

counts

missing mass (GeV)
Modeling of FSI

\[
\tilde{M}_{fi} = \frac{\psi(kr + \delta)}{\psi(kr)} M_{fi},
\]

\[
\left(\frac{d\sigma}{d\Omega}\right)_{FSI} = \int_{P.S.} |\tilde{M}_{fi}|^2 = \int_{P.S.} \left| \frac{\psi(kr + \delta)}{\psi(kr)} \right|^2 |M_{fi}|^2
\]

\[
I = \left| \frac{\psi^*(kr + \delta)}{\psi(kr)} \right|^2
\]
Ln Potential Parametrization

\[ V(r) = V_A e^{r^2/\beta^2_A} + V_R e^{r^2/\beta^2_R} \]

<table>
<thead>
<tr>
<th>Model</th>
<th>state</th>
<th>( V_A ) (MeV)</th>
<th>( \beta_A ) (fm)</th>
<th>a (fm)</th>
<th>r (fm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Verma</td>
<td>Singlet ((^1S_0))</td>
<td>-167.34</td>
<td>1.100</td>
<td>-2.29</td>
<td>3.15</td>
</tr>
<tr>
<td></td>
<td>Triplet ((^3S_1))</td>
<td>-132.42</td>
<td>1.100</td>
<td>-1.77</td>
<td>3.25</td>
</tr>
<tr>
<td>Jülich A</td>
<td>Singlet ((^1S_0))</td>
<td>-373.94</td>
<td>0.790</td>
<td>-1.60</td>
<td>1.33</td>
</tr>
<tr>
<td></td>
<td>Triplet ((^3S_1))</td>
<td>-144.14</td>
<td>1.059</td>
<td>-1.60</td>
<td>3.15</td>
</tr>
<tr>
<td>Jülich B</td>
<td>Singlet ((^1S_0))</td>
<td>-131.49</td>
<td>1.095</td>
<td>-0.57</td>
<td>7.65</td>
</tr>
<tr>
<td></td>
<td>Triplet ((^3S_1))</td>
<td>-189.60</td>
<td>0.964</td>
<td>-1.94</td>
<td>2.42</td>
</tr>
</tbody>
</table>

Table 5.9: The parameters for the various potentials used in Eq. 5.11. The strength and range of the repulsive part are fixed for all three potentials at \( V_R = 246.80 \) MeV, \( \beta_R = 0.82 \) fm for the singlet state, and \( V_R = 181.68 \) MeV, \( \beta_R = 0.82 \) fm for the triplet state. From [8].
Ln FSI from $^2\text{H}(e,e'K^+)$
Singlet

Triplet
$^{2}\text{H}(e,e'K^+)\gamma\text{N}$

Counts vs. missing mass (GeV)

Graph showing data points and fitted curves for various reactions:
- Quasifree Monte Carlo
- $d(e,eK^+)\Lambda^0n$
- $d(e,eK^+)(\Sigma^0n$
- $d(e,eK^+)\Sigma^-p$
- $\Lambda^0n + \Sigma^0n + \Sigma^-p$

Annotated with thresholds and peak analyses.
\[ R_\Lambda = \frac{\frac{d\sigma}{d\Omega} (\gamma d \rightarrow K^+\Lambda)}{\frac{d\sigma}{d\Omega} (\gamma p \rightarrow K^+\Lambda)} \]

\[ R_\Sigma = \frac{\frac{d\sigma}{d\Omega} (\gamma d \rightarrow K^+\Sigma)}{\frac{d\sigma}{d\Omega} (\gamma p \rightarrow K^+\Sigma^0)} \]

**t-channel:**

\[ g_{K^+\Sigma^-n} = \sqrt{2} g_{K^+\Sigma^0p} \quad R_\Sigma = 3 \]

**s-channel:**

\[ G_{K^+\Sigma^-\Delta^0} = G_{K^+\Sigma^0\Delta^+/\sqrt{2}} \]

\[ R_\Sigma = 1.5 \]

Bayarshi et al., Phys. Lett. 34B, 547 (1971)

this experiment
Measurement of $R_\Sigma$ at large $W$

Jörg Reinhold

June 8, 2002

The $(e,e'K^+)$ reaction on deuterium produces $\Lambda$, $\Sigma^0$, and $\Sigma^-$ hyperons. In a quasifree picture, the $\Lambda$ and $\Sigma^0$ are produced of the proton, and the $\Sigma^-$ is produced of the neutron. Isospin conservation at the hadronic vertices predicts for the ratio total $\Sigma$ production of deuterium ($\Sigma^0 + \Sigma^-$) to $\Sigma^0$ production of hydrogen,

$$R_\Sigma = \frac{\frac{d\sigma}{d\Omega}(\gamma d \rightarrow K^+\Sigma^-)}{\frac{d\sigma}{d\Omega}(\gamma p \rightarrow K^+\Sigma^0)},$$

values of $R_\Sigma = 3$ for $t$-channel and $R_\Sigma = 1.5$ for $s$-channel. Photoproduction experiments performed in the 70s measured values of $R_\Sigma = 2.37 \pm 0.11 \pm 0.12$ [1] and $R_\Sigma = 2.73 \pm 0.18$ [2] for $W = 4.6$ GeV and $W = 5.6$ GeV, respectively. Jefferson Lab experiment E91-016 measured $R_\Sigma = 1.6$ for $W = 1.9$ GeV. The only earlier electroproduction experiment averages at $R_\Sigma = 1.89$ for $W = 2.4$ GeV, but, suffers from large errors. All the results are summarized in Fig. 1. An almost linear increase of $R_\Sigma$ with $W$ is observed. Therefore, $R_\Sigma$ could be a measure of the evolution of the reaction mechanism from primarily $s$-channel at low $W$ to primarily $t$-channel at high $W$. The existing data, however, don’t cover the transition region. The goal of this proposal is to measure $R_\Sigma$ from close to threshold to the maximum $W$ accessible with the proposed Hall C equipment. With 11 GeV beam energy, a maximum of $W = 3.6$ GeV is reached for $Q^2 = 1.4$ GeV$^2$. At somewhat lower $W$ L/T separations are kinematically accessible. This should also be explored. A measurement of $R_\Sigma$ up to the maximum possible $W$ combined with an L/T separation at lower $W$ could determine the kinematic range over which longitudinal components dominate the reaction mechanism. This could guide experiments which strongly depend on the assumption of longitudinal mechanisms, like meson form factor measurements.
Bound $\Lambda$-Hypernuclear States for He

$A=3$

$^3\Lambda H$  \hspace{1cm} $B = 130$ keV, $J^\pi = (1/2)^+$ (Hypertriton)

$A=4$

$^4\Lambda He$  \hspace{1cm} $B_{\text{ground}} (0^+) = 2.93 \pm 0.03$ MeV  \hspace{1cm} $B_{\text{excited}} (1^+) = 1.24 \pm 0.06$ MeV

$^4\Lambda H$  \hspace{1cm} $B_{\text{ground}} (0^+) = 2.04 \pm 0.04$ MeV  \hspace{1cm} $B_{\text{excited}} (1^+) = 1.00 \pm 0.06$ MeV

Different Production Mechanism:

$(K,\pi)$ negligible spin flip strength, good momentum matching, may populate substitutional states

$(\pi,K)$ substantial momentum transfer, may excite higher spin states, spin flip strength

$(\gamma^*,K)$ Electroproduction: Large momentum transfer, large spin flip strength
$^3,^4\text{He}(e,e'K^+)$

Counts

Counts

$3^\circ$

$6^\circ$

$12^\circ$

$4^\circ$

LH
Bound L-Hypernuclei $A=4$

$\gamma _v^4\text{He} \rightarrow K \rightarrow ^4H_A$

Kaon-photon angle

H($e,e'K$) Angular Distribution

Kaon-photon angle
Cross section is kinematic factor times overlap integral times elementary cross section

\[ \frac{d\sigma_T}{d\Omega_K} = \frac{1}{6} W_A^2 |F(Q)|^2 \left( \frac{d\sigma_T}{d\Omega_K} \right)_{\text{proton}}, \]

\[ F(Q) = \int d^3 q d^3 p \psi_{^3\text{He}}^3(p, q + \frac{2}{3}Q) \psi_{^3\text{He}}^3(p, q) \]

\[ W_A = \sqrt{\frac{|q_{^3\text{He}}^{c.m.}|^3_{^3\text{He}} |k_{^3\text{He}}^{c.m.}|_p M_{^3\text{He}} E_{^3\text{He}} W_p}{m_p E_A W_{^3\text{He}}^2}}. \]

Fig. 4. Differential cross section for kaon photoproduction off the proton and $^3\text{He}$ as function of kaon angle. The elementary reaction (dotted line) is taken from Ref. [32] and the corresponding experimental datum is from Ref. [35]. The dashed line shows the approximation for production off $^3\text{He}$ calculated from Eq. (32), the solid line represents the exact calculation using $S$-waves.
H(e,e'p)w: Pawel Ambozewicz

Diagram: Graph showing data points and fitted curves with various kinematic variables such as $\langle W \rangle = 1.75$ GeV and $\langle Q^2 \rangle = 0.5$ GeV. The legend explains different data sets and fits, including variable $\varphi'$ ranges, DESY 1977, and models from Fraas (1971) and O. Zhao Model (2005).
$^{12}\text{C}, ^{27}\text{Al}(e,e'\ell K)$: Wendy Hinton's analysis
Summary

First d(e,e'K) with good resolution
\[ R_L = 1 \implies \text{quasifree production mechanism} \]
\[ R_S = 1.6 \implies \text{S production s-channel dominated} \]
First ever A(e,e'K) for A>2
\[ ^4\text{He}(e,e'K)^4LH \text{ qualitatively shows formfactor} \]

Outlook

- HNSS achieved 1 MeV resolution
- Hall A will take data early 2004 (Franco Garibaldi, Saturday)
- New hypernuclear spectrometer HKS will take data later in 2004 (S.N. Nakamura, Saturday)
- The HKS collaboration is considering the use of cryogenic targets for future few-body studies
E91-016 Collaboration


aFlorida International University, bThomas Jefferson National Accelerator Laboratory, cArgonne National Laboratory, dNC A&T State University, eKent State University, fHampton University, gTemple University, hCollege of William and Mary, iCalifornia Institute of Technology, jYerevan Physics Institute, kUniversity of Maryland, lUniversity of Virginia, mJuniata College, nForschungszentrum Rossendorf, oNorthwestern University, pSouthern University at New Orleans, qUniversity of Pennsylvania, rTohoku University, sUniversity of Minnesota, tOld Dominion University, uAmerican University, vOhio University, wThe George Washington University, xRensselaer Polytechnic Institute, yUniversity of Houston, zDuke University, +University of Illinois
THE END