Electroproduction of the Λ hyperon on the proton

Workshop on Perspectives of high resolution hypernuclear spectroscopy at JLab

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electroproduction

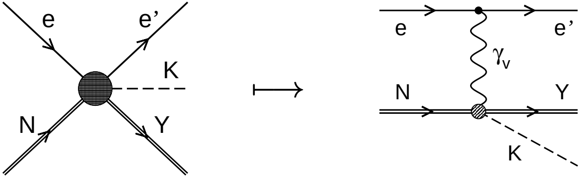
$$e + p \longrightarrow e' + K^+ + \Lambda \qquad I_{K\Lambda} = \frac{1}{2}$$
$$e + p \longrightarrow e' + K^+ + \Sigma^0 \qquad I_{K\Sigma} = \frac{1}{2}, \frac{3}{2}$$
$$e + p \longrightarrow e' + K^0 + \Sigma^+$$
$$e + n \longrightarrow e' + K^0 + \Lambda \qquad I_{K\Lambda} = \frac{1}{2}$$
$$e + n \longrightarrow e' + K^0 + \Sigma^0 \qquad I_{K\Sigma} = \frac{1}{2}, \frac{3}{2}$$
$$e + n \longrightarrow e' + K^+ + \Sigma^-$$

(virtual)photoproduction – a simpler process

$$\gamma_{(v)} + N \longrightarrow K + Y$$

Description of electroproduction

- the electromagnetic part of the process is well known
- the coupling constant is small $\alpha = \frac{e^2}{2\pi} \doteq \frac{1}{137} \ll 1$
  $\rightarrow$ the one-photon approximation:



- no Coulomb distortion of e and e′
  – important for electroproduction on heavy nuclei
- leptonic and hadronic parts can be separated
- photoproduction is not a limit case of electroproduction ($q^2 \rightarrow 0$)

- kinematics

  $E_e,\ \ E'_e,\ \ \theta_e,\quad \theta_K,\ \ \Phi_K$

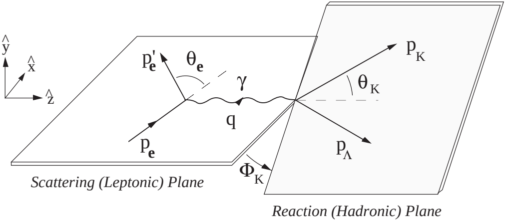
  $Q^2 = -q^2,\ \ \epsilon = \left(1 + \frac{2\,\vec{q}^2}{-q^2}\tan^2\frac{\theta_e}{2}\right)^{-1},\ s = (q + p_p)^2,\ t = (q - p_K)^2,\ \ \Phi_K$

  $\sqrt{s} = W \in (\,W_{thr},\ 2.6\,)\ \mathrm{GeV},\quad W_{thr} = 1.609\ \ \text{for}\ \ K\Lambda$

- the unpolarized cross section

$$\frac{d^5\sigma}{dE'_e\, d\Omega'_e\, d\Omega_K} = \Gamma\left[\frac{d\sigma_T}{d\Omega_K} + \epsilon\,\frac{d\sigma_L}{d\Omega_K} + \epsilon\,\frac{d\sigma_{TT}}{d\Omega_K}\cos 2\Phi_K + \sqrt{2\epsilon(1+\epsilon)}\,\frac{d\sigma_{TL}}{d\Omega_K}\cos\Phi_K\right]$$

- in Laboratory frame:



Motivation

- Which degrees of freedom are relevant? *partons* $\leftrightarrow$ *hadrons*
- non perturbative regime of QCD: *quark models* $\leftrightarrow$ *isobar models*
- many opened channels $\rightarrow$ channel couplings, unitarity, final-state interaction
  multi-channel $\leftrightarrow$ *single-channel analysis*
- description of the background part: $f = f_{bgr} + f_{res}$
  isobar $\leftrightarrow$ *Regge approach*
- effective Lagrangian approach
  - properties of baryon resonances in the 3rd resonance region ($E_\gamma^{lab} \geq 1$ GeV)
    $\rightarrow$ parameters, structure, existence (missing states)
  - $SU(3)_f$ symmetry: $g_{\pi NN} \leftrightarrow g_{K\Lambda N}$
  - dynamics of the process – important resonances N^*, Y^*, K^*
  - a satisfactory description of the process at small angles
    $\rightarrow$ an input in hypernucleus calculations
- plenty of new experimental data
- studying all channels is important – neutron target, production of K^0

K^+ production in the small-angle region

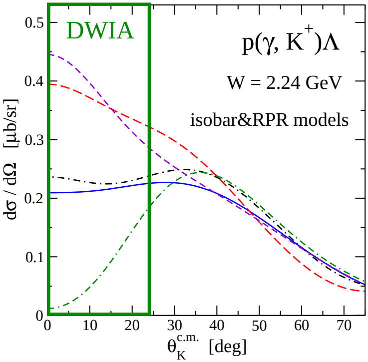
- the elementary amplitude is an input in DWIA ⇒ a good description of the elementary process is important for reliable predictions of the hypernucleus-production cross sections

DWIA *(frozen-nucleon approx.)*:

$$\langle \Psi_H | \sum_i \chi_\gamma \chi_K^* \mathcal{J}^\mu(i)\, | \Psi_A \rangle$$

$\mathcal{J}^\mu$ – elementary hadron current in lab frame

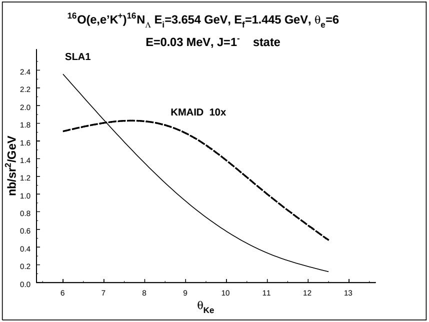
– the main contribution of $\mathcal{J}^\mu$ is from **a small θ_K region**

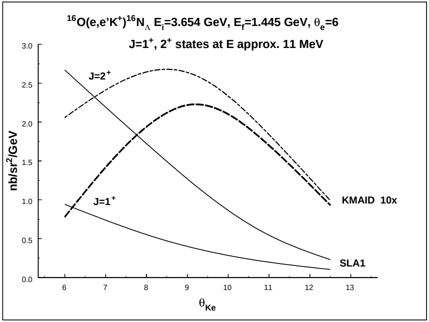


- vice versa: the hypernucleus-production cross sections can be used to test the elementary models in the small-angle region

Angular dependence of the hypernucleus cross section

- electroproduction of $^{16}\mathrm{N}_\Lambda$ ($E_\gamma^{lab} = 2.21$ GeV, $\theta_e^{lab} = 6^o$)
  $\rightarrow$ magnitudes differ by factor of 10
- generally a steeply decreasing dependence, the slope depends on the spin (J)
- the angular behaviour depends on the spin structure of the elementary amplitude at small θ_K $\rightarrow$ more detailed information about the amplitude





Methods of description

- single-channel analysis
  - Isobar model
    – effective hadronic Lagrangian description
    – Adelseck-Saghai, Williams-Ji-Cotanch, Saclay-Lyon, Kaon-MAID, Gent isobar, Maxwell
  - Regge-plus-resonance model
    – hybrid isobar-Regge description
    – Gent group: RPR-2007, RPR-2011
  - multipole analysis – Mart and Sulaksono
- multi-channel analysis
  - unitary isobar approach (coupled channels)
    – Giessen, Bonn-Gatchina, Dubna-Mainz-Taipei, Julia-Diaz et al, Usov et al, Shyam et al
  - partial-wave analysis – SAID
  - chiral unitary framework
    – chiral Lagrangian, coupled channels, threshold region
    – Borasoy et al
- Quark model – resonances included; Close, Zhenping Li et al

Isobar model

- meson-baryon FSI is neglected (channel couplings, re-scattering)
  $\rightarrow$ one-channel approximation: $T = V + V\ G\ t$
  - violation of unitarity
  - effective coupling constants include a part of the FSI effects
- driving term V:
  - effective hadron Lagrangian (fields, couplings, resonances, form factors)
  - tree-level perturbation expansion $\Rightarrow$ s-, t-, and u-channel exchanges; contact term (gauge invariance)
  - a set of relevant resonances in the intermediate states has to be selected (3rd resonance region: heavy, high-spin, or missing resonances)
  - free parameters are fitted to data ($\approx 10 - 20$ parameters)
  - many sets of resonances with a good χ^2 can be chosen
    $\Rightarrow$ large number of possible models $\Rightarrow$ constraints or better data analysis
- constraints on the models:
  - SU(3) symmetry: $-4.4 \le g_{KN\Lambda}/\sqrt{4\pi} \le -3.0 \qquad 0.8 \le g_{KN\Sigma}/\sqrt{4\pi} \le 1.3$
  - crossing symmetry: description of $\Gamma(K^- p \longrightarrow \gamma\,\Lambda)$

Isobar model

- large contributions to the background part of the amplitude from the Born diagrams are reduced:
  - hadronic form factors – gauge invariance → a contact term
    – inclusion of a hadron structure
    – dipole, Gauss, multidipole-Gauss (high spin) form
    – which cut-off parameter: hard × soft?
  - hyperon resonances in u channel – which are relevant?
  - hadronic form factors + hyperon exchanges
  - this problem is avoided in the Regge-plus-resonance model
- the resonant part: s-channel exchanges of the nucleon resonances

  (resonance width in the Feynman propagator → partial restoration of unitarity)
- electroproduction (Q^2 dependence)
  - electromagnetic form factors (gauge invariance)

    – EVDM (electron scattering data) for γNN and QM for the γNN^* transitions
  - couplings of baryon fields to the photon transversal modes
  - couplings to the longitudinal mode of the virtual photon

    $\overline{\psi}_{N^*} \Gamma \gamma^\nu \psi_N \, \partial^\mu F_{\mu\nu}$ (spin 1/2) $\quad \overline{\psi}^{\,\nu}_{N^*} \Gamma \psi_N \, \partial^\mu F_{\mu\nu}$ (spin 3/2)

    ⇒ the coupling constants have to be determined in electroproduction

Regge-plus-resonance model

Invariant amplitude: $\mathcal{M} = \mathcal{M}_{bgr}(Regge) + \mathcal{M}_{res}(isobar)$

- the background part - exchanges of degenerate K and K* trajectories

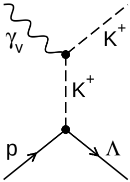
$$\mathcal{M}_{bgr}(s,t) = \mathcal{P}^{K}_{Regge}(s,t) \times \beta_K(s,t) + \mathcal{P}^{K^*}_{Regge}(s,t) \times \beta_{K^*}(s,t)$$
$$+ \mathcal{M}^{p,elec}_{Feyn} \times \mathcal{P}^{K}_{Regge}(s,t) \times (t - m_K^2)$$

  - the Regge propagator

$$\mathcal{P}^{x}_{Regge}(s,t) = \frac{(s/s_0)^{\alpha_x(t)}}{\sin\pi\,\alpha_x(t)} \frac{\pi\,\alpha'_x}{\Gamma(1+\alpha_x(t))} \left\{ \begin{array}{c} 1 \\ e^{-i\pi\alpha_x(t)} \end{array} \right\}$$

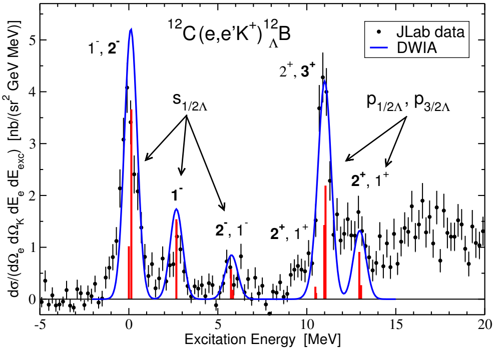
  - the Regge trajectories: $\alpha_x(t) = \alpha'_x(t - m^2)$, $x = \mathrm{K}, \mathrm{K}^*$
  - the residue of the lowest pole

for $t \to m_K^2$ $\quad \mathcal{P}^{K}_{Regge}(s,t) \times \beta_K(s,t) \longrightarrow \dfrac{\beta_K(s,t)}{t - m_K^2}$



- only 3 parameters fixed by high-energy data (W>2.6 GeV)

Electroproduction of hypernuclei



data: JLab Hall A
exp. E94-107

$E_\gamma^{lab} = 2.21$ GeV

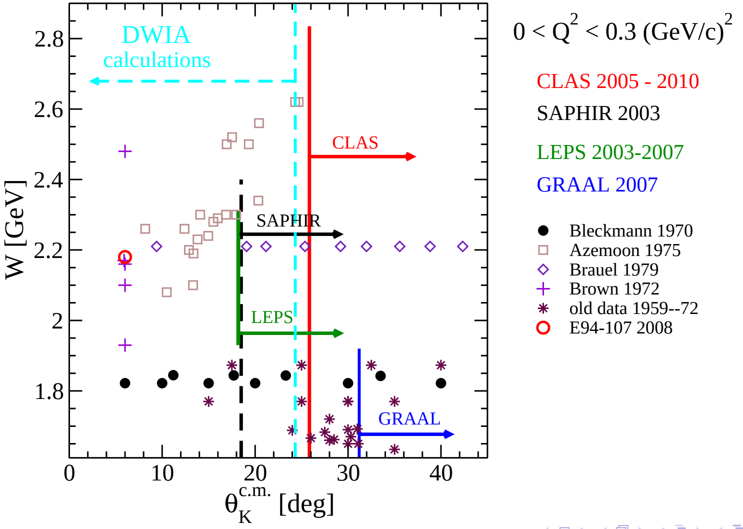
$\theta_e^{lab} = \theta_K^{lab} = 6^o$

$Q^2 = 0.018\ (GeV/c)^2$

calculations with
the Saclay-Lyon model

- in DWIA the elementary hadron current significantly contributes only for small θ_K and experiments are done at very small Q^2
  $\Rightarrow$ **predictions of isobar models have to be reliable for small θ_K and Q^2**
- $\sigma_{TT} \sim \sin^2\theta_K$, $\sigma_{TL} \sim \sqrt{Q^2}\, \sin\theta_K$, and $\sigma_L \sim Q^2$
  $\Rightarrow$ σ_T ($\Leftrightarrow$ photoproduction cross section) should dominate (unpolarized case)
  $\Rightarrow$ the models could be well determined by the photoproduction data

World data for small θ_K and Q^2 kinematics

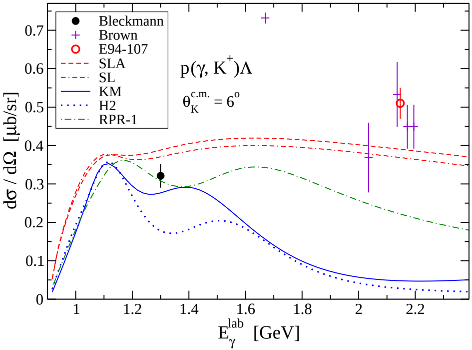


Predictions of isobar and RPR models differ at very small θ_K and Q^2

- photoproduction (σ_T) dominates the electroproduction cross section

$$\sigma = \sigma_T + \epsilon\,\sigma_L + \epsilon\sigma_{TT} + \sqrt{2\epsilon(1+\epsilon)}\sigma_{TL}, \quad \Phi_K = 0$$

SL: $0.41 = 0.35 + 0.004 - 0.001 + 0.06$ (ϵ=0.7, θ_K=6°, Q^2=0.07 $(GeV/c)^2$)



Electroproduction data:

Brown72 [PRL28(1972)1086]

$\sigma = \sigma_T + \epsilon\sigma_L$

W = 1.93 ÷ 2.17 GeV

Q^2 = 0.18 and 0.29 $(GeV/c)^2$

$\theta_K^{c.m.}$ = 5.9° and 6°

E94-107 (JLab, Hall A)

W = 2.2 GeV

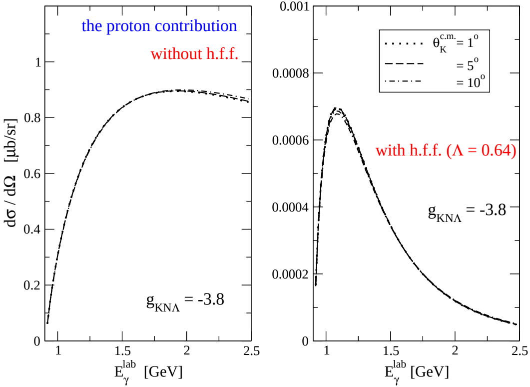
Q^2 = 0.07 $(GeV/c)^2$

$\theta_K^{c.m.}$ = 6°

- Isobar model H2: $N^* - S_{11}(1650), P_{11}(1710), P_{13}(1720), D_{13}(1895)$; $Y^* - S_{01}(1670), S_{01}(1800)$; hadronic form factors; fit to CLAS and LEPS data
- Regge-plus-resonance model RPR-1: $N^* - S_{11}(1535)\ S_{11}(1650), P_{11}(1710), P_{13}(1720), D_{13}(1895)$; multidipole-Gauss hadronic f.f.; fit to CLAS and LEPS data.

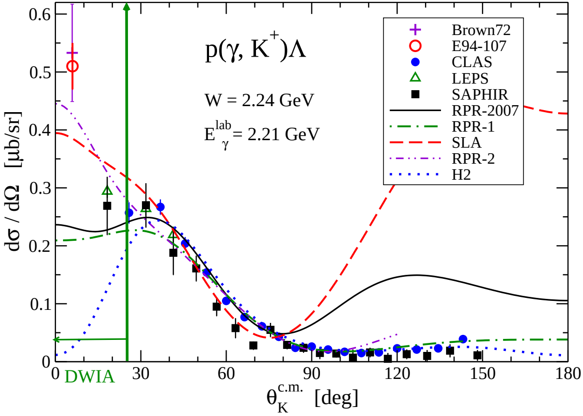
Supression of $\sigma(\theta)$ at small θ_K due to the hadronic form factors

- The proton exchange:
  - contributes to the background part of the amplitude
  - is important contribution at small θ_K
  - is suppressed by hadronic form factors, e.g. in KM and H2 models
  - is not suppressed in SL and RPR models



The angular dependence by isobar and RPR models

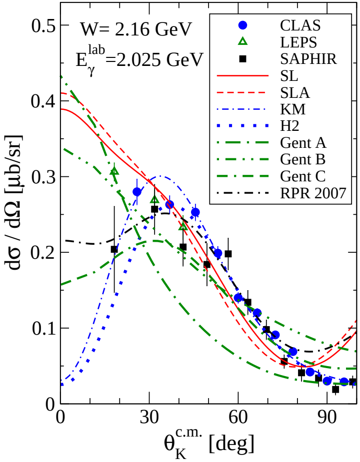
- H2 and RPR-1 fitted to CLAS and LEPS data ⇒ a good agreement for $30^\circ < \theta_K < 150^\circ$
- for $\theta_K < 30^\circ$ H2 suppressed by the hadronic form factor
- no suppression of the background part for the RPR-1 and SLA models
- SLA preffered by the hypernucleus data: DWIA calculations of ${}^{12}_{\Lambda}$B, ${}^{16}_{\Lambda}$N, and ${}^{9}_{\Lambda}$Li



RPR-2 was fitted only to $0^\circ < \theta_K < 90^\circ$

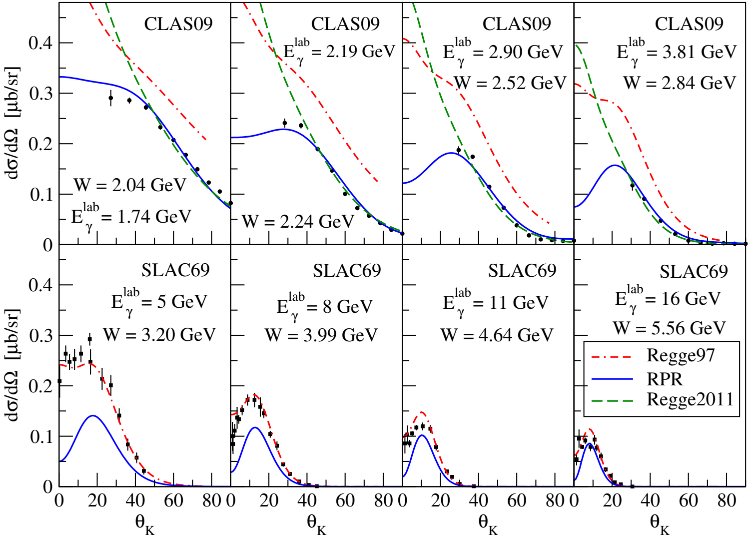
	RPR-1	RPR-2
$g_{K\Lambda p}$	-1.4	-3.0
G^V_{K*}	-0.30	0.19
G^T_{K*}	-1.80	0.31

The angular dependence by isobar and RPR models



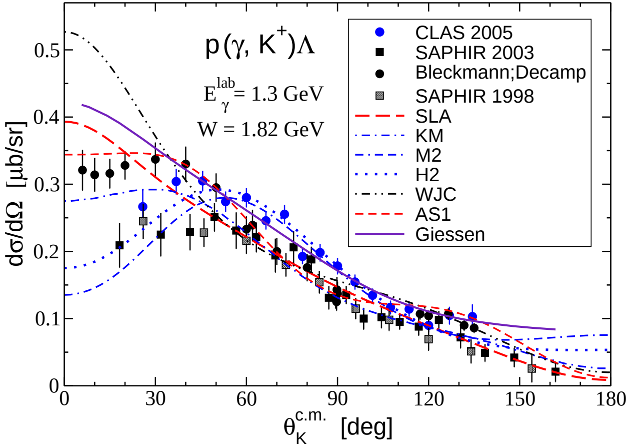
- note inconsistency of CLAS and SAPHIR data at $\theta \approx 20^\circ$
- H2 fits very well the CLAS data but it fails for $\theta_K < 30^\circ$
  $\Rightarrow$ the CLAS data alone cannot fully determine the angular dependence of models
- Gent A, B, and C differ in the Λ_{cut}^{bgr}: 0.413, 1.538, and 1.856, respectively
- the hypernucleus electroproduction cross sections suggest that SL gives right predictions of the elementary cross section
  $\rightarrow$ a forward-peaked cross section?

The very forward angular dependence above the resonance region



The angular dependence near threshold by isobar and Giessen models

- data inconsistency for $\theta_K < 50^\circ$
- the Giessen model is consistent rather with SL than with H2, M2 or KM for $\theta_K < 30^\circ$



Summary

- the calculations of hypernucleus electroproduction cross sections in DWIA require a proper understanding of the elementary process in the small θ_K and Q^2 kinematical region;
- predictions of the isobar and Regge-plus-resonance models for the cross sections still significantly differ in this kinematical region due to lack of data;
- the ample world data (CLAS, SAPHIR, LEPS,..) on the process cover mainly the region $\theta_K > 20^\circ$ which is not enough to fully determine the angular dependence of the elementary cross section;
- new good quality data at very small θ_K and Q^2 are needed to test the models which then will be able to provide more reliable predictions of the cross sections for electroproduction of hypernuclei;
- the small-angle data can contribute to revealing dynamics of the models, e.g. the background description, a role of the hyperon resonances, hadronic form factors (Λ_{cut}).