The elementary reaction for electroproduction of hypernuclei in DWIA

Workshop on ^{208}Pb(e,e'K$^+$) and neutron stars

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- production of hypernuclei by virtual photons (one-photon approximation)

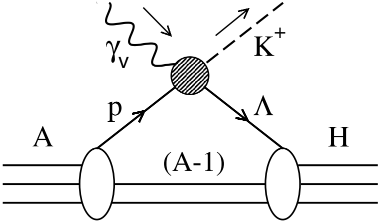
  $\gamma_v + \mathrm{A} \longrightarrow \mathrm{H} + \mathrm{K}^+$

- in impulse approximation

  $\langle \Psi_\mathrm{H} | \sum_j \chi_\gamma \chi^*_\mathrm{K} \mathcal{J}^\mu_j \, | \Psi_\mathrm{A} \rangle$

  $\mathcal{J}^\mu_j$ – elementary production current on the j^{th} proton

  – see also talk of Omar Benhar



The elementary production $\mathrm{e} + \mathrm{p} \longrightarrow \mathrm{e}' + \Lambda + \mathrm{K}^+$

- one-photon approximation: $\gamma_\mathrm{v} + \mathrm{p} \longrightarrow \Lambda + \mathrm{K}^+$
- open-strangeness production in the 3rd resonance region ($\sqrt{s_{thr}} = 1.61$ GeV)
  $\rightarrow$ a complex reaction mechanism: many (missing) resonances, background
- open channels coupled via the meson-baryon FSI
  $\rightarrow$ unitarity: *multi-channel* $\leftrightarrow$ *single-channel approach*
- isobar approach – a phenomenological description in the resonance region
  $\rightarrow$ *an effective Lagrangian* with baryon, meson, and photon fields
  $\rightarrow$ *the tree-level approximation*
  $\rightarrow$ a structure of hadrons – *form factors*
- single-channel analysis (FSI neglected)
  $\rightarrow$ isobar model: Adelseck-Saghai (90), Williams-Ji-Cotanch (92), Saclay-Lyon (96), Kaon-MAID (99), Gent isobar (01), Maxwell (07)
  $\rightarrow$ Regge-plus-resonance model (hybrid isobar-Regge description):
  Gent group: RPR-2007, RPR-2011
- many experimental data points after 2004 – more than 7000 data

Isobar model

D. Skoupil, P. Bydžovský, Phys. Rev. C 93, 025204 (2016); 97, 025202 (2018)

- single-channel approach – final-state interactions not included
  - the amplitude for $\Lambda K \longrightarrow \Lambda K$ not known experimentaly
  - violation of unitarity
  - fitted coupling constants can include a part of the FSI effects
  - energy dependent widths of N^* → *a partial restoration of unitarity*

- effective hadron Lagrangian
  - ground-state hadrons, N^*, Y^*, and K^* resonances → couplings
  - high-spin states: $N^*(3/2, 5/2)$ and $Y^*(3/2)$
  - a set of relevant resonances has to be selected in the analysis
  - hadron form factors included in a gauge-invariant way (a contact term)
  - tree-level expansion: s-channel exchanges (N^*– resonant contributions); t- and u-channel exchanges and a contact term (non resonant terms)
  - $g_{KN\Lambda}$ and $g_{KN\Sigma}$ are constrained by $SU(3)_f$ symmetry
  - free parameters are fitted to data (≈ 25 – 30 param. ⇔ 3400 data points)

Isobar model

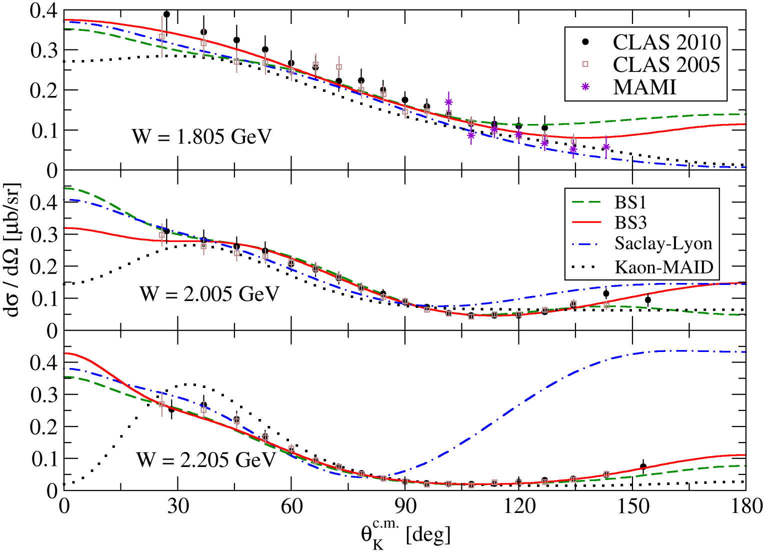
- considered resonances
  - t-channel: $K^*(892)$, $K_1(1272)$ with the vector and tensor couplings
  - s-channel: N* with mass ≤ 2 GeV and spin $\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$ motivated by the Bayesian analysis (RPR) [L.De Cruz etal, Phys.Rev.C86(2012)015212] and five more states from PDG
  - missing resonances $D_{13}(1875)$, $P_{11}(1880)$, $P_{13}(1900)$
  - u-channel: nine Y* with spin $\frac{1}{2}$ and $\frac{3}{2}$ and mass < 2 GeV
- hadron form factors:
  dipole, multidipole, Gauss, and multidipole-Gauss
- about 30 free parameters
  - $g_{K\Lambda N}$, $g_{K\Sigma N}$
  - G_V and G_T for K^* and K_1
  - spin-$\frac{1}{2}$ resonances (N^* or Y^*) $\rightarrow$ 1 parameter
  - spin-$\frac{3}{2}$ and $\frac{5}{2}$ resonances $\rightarrow$ 2 parameters
  - 2 cut-off parameters for the hadron form factors (resonant, background)

Isobar model

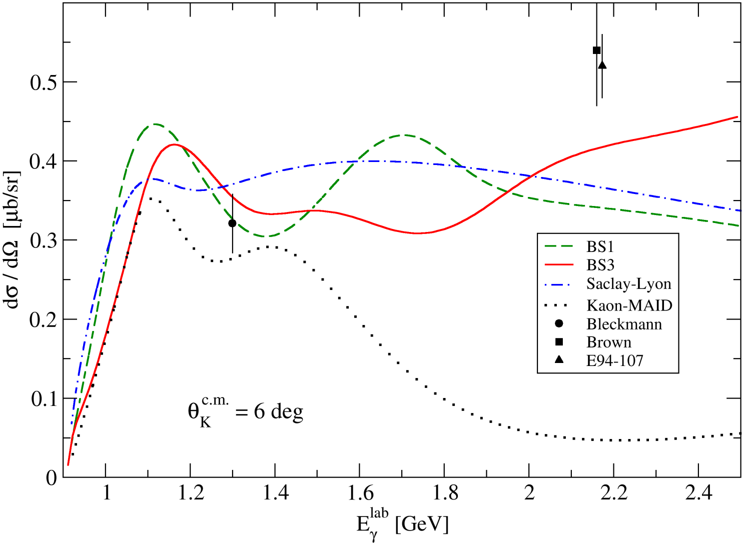
- experimental data for $W < 2.36$ GeV
  - cross sections: CLAS 2005, 2010; LEPS; old data (Adelseck,Saghai)
  - hyperon polarization: CLAS 2010
  - beam asymmetry: LEPS
  - all together $\approx$ 3400 data points
  - experimental uncertainty used in fitting: $\Delta\sigma_{tot} = \sqrt{\Delta\sigma^2_{stat} + \Delta\sigma^2_{syst}}$
- solutions: BS1 and BS2 for photoproduction and
  BS3 for electroproduction
- selected resonances in model BS1:
  $S_{11}(1535)$, $S_{11}(1650)$, $F_{15}(1680)$, $P_{13}(1720)$, $F_{15}(1860)$, $D_{13}(1875)$, $P_{13}(1900)$, $F_{15}(2000)$; $\Lambda(1520)$, $\Sigma(1660)$, $\Sigma(1750)$, $\Lambda(1800)$, $\Lambda(1890)$, $\Sigma(1940)$; $K^*(892)$, $K_1(1270)$
- hadron form factors:
  multidipole with $\Lambda_{bgr} = 1.88$ GeV and $\Lambda_{res} = 2.74$ GeV

Results with isobar models for photoproduction

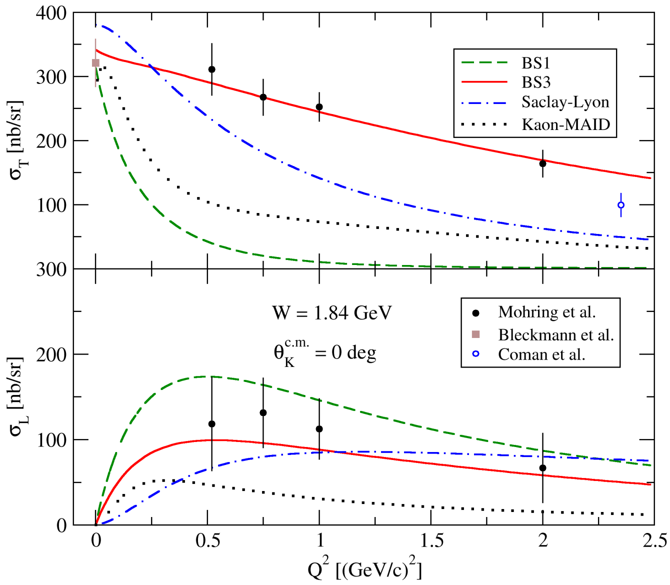
[D.Skoupil, P.Bydžovský Phys.Rev.C97,025202(2018)]



Results at small angles are important for hypernucleus calculations

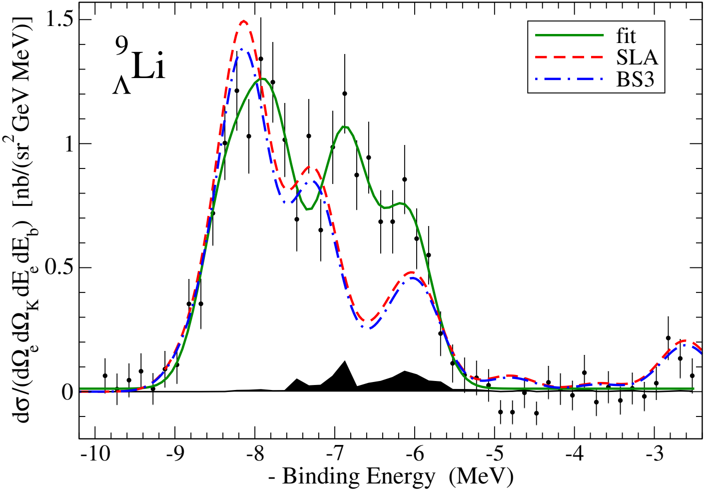


Results for electroproduction



Predictions for electroproduction of hypernuclei

DWIA calculations and the data [F.Garibaldi et al, Phys. Rev. C 99, 054309 (2019)]



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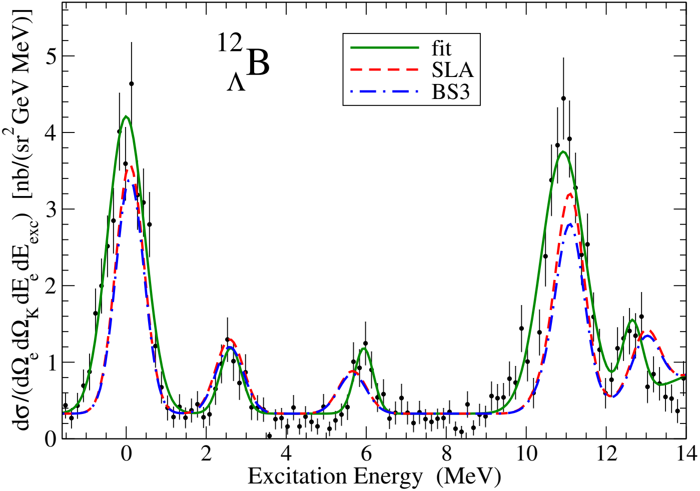


Electroproduction versus photoproduction DWIA results

- the unpolarized laboratory cross section in electroproduction

$$\frac{d^3\sigma}{dE'_e\, d\Omega'_e\, d\Omega_K} = \Gamma \left[\frac{d\sigma_T}{d\Omega_K} + \epsilon \frac{d\sigma_L}{d\Omega_K} + \epsilon \frac{d\sigma_{TT}}{d\Omega_K} + \sqrt{2\epsilon(1+\epsilon)} \frac{d\sigma_{TL}}{d\Omega_K} \right]$$

- $d\sigma_T$ dominates for a very small Q^2 (an almost real transversal photon)
- JLab experiment E94-107: $E_\gamma^{lab} = 2.21$ GeV, $\theta_{Ke}^{lab} = 6^\circ$, $\theta_{K\gamma}^{lab} = 1.8^\circ$, $\epsilon = 0.703$, and $Q^2 = 0.0644\ (\mathrm{GeV/c})^2$ $\rightarrow$ photoproduction ?

$^{12}\mathrm{C}(e, e'K^+)^{12}_{\Lambda}\mathrm{B}$ with the Saclay-Lyon A model:

E	J_H^P	$\theta_{K\gamma}^{LAB}$	$d\sigma$	$d\sigma_T$	$\epsilon d\sigma_L$	$\epsilon d\sigma_{TT}$	$\sqrt{2\epsilon(1+\epsilon)}d\sigma_{TL}$	$d^3\sigma$
0.0	1^-	1.8	36.768	42.505	0.251	0.040	-6.028	0.640
0.116	2^-	1.8	127.898	148.198	1.083	0.364	-21.747	2.227

$\rightarrow$ the transverse-longitudinal interference terms contribute more than 10%

Regge-plus-resonance model for $K\Lambda$ photoproduction

[P. Bydžovský and D. Skoupil, Phys. Rev. C 100, 035202 (2019)]

Invariant amplitude

$$\mathcal{M} = \mathcal{M}_{bgr}(Regge) + \mathcal{M}_{res}(isobar) + \mathcal{M}_{int}(gauge\ invariance)$$

- the resonant part: exchanges of N^* in s-channel like in the isobar model – selected N^*:

  $S_{11}(1535)$, $S_{11}(1650)$, $D_{15}(1675)$, $F_{15}(1680)$, $D_{13}(1700)$, $F_{15}(1860)$, $P_{11}(1880)$, $D_{13}(1875)$, $P_{13}(1900)$, $D_{13}(2120)$

- regularization of the resonant part: multidipole hadron form factors

- the contact term: the gauge-restoration method by Haberzettl et al, Phys.Rev.C 92, 055503 (2015) $\rightarrow$ the proton exchange is not included.

Regge-plus-resonance model

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

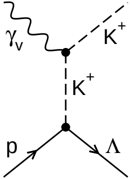
$$\mathcal{M}_{bgr} = \mathcal{P}^{K}_{Regge}(s,t) \times \beta_K + \mathcal{P}^{K^*}_{Regge}(s,t) \times \beta_{K^*}$$

  - the Regge propagator with the rotating phase

$$\mathcal{P}^{x}_{Regge}(s,t) = \frac{(s/s_0)^{\alpha_x(t)}}{\sin\pi\,\alpha_x(t)}\,\frac{\pi\,\alpha'_x\,\mathrm{e}^{-i\pi\alpha_x(t)}}{\Gamma(1+\alpha_x(t))}\,, \quad \alpha_x(t) = \alpha'_x(t-m^2), \quad x = \mathrm{K}, \mathrm{K}^*$$

  - the residue of the lowest pole

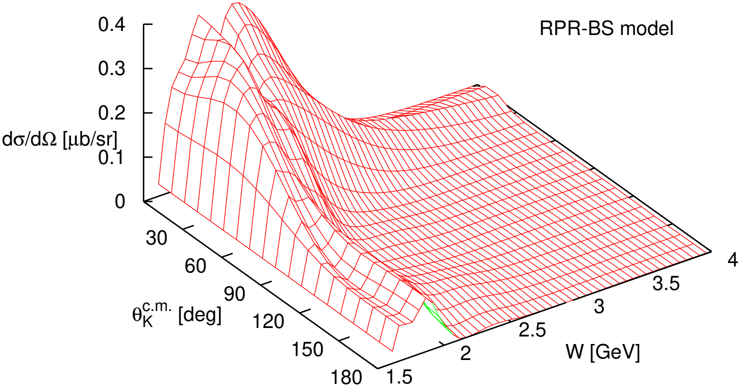
for $t \to m_K^2$ $\quad \mathcal{P}^{K}_{Regge}(s,t) \times \beta_K \longrightarrow \frac{\beta_K}{t - m_K^2}$



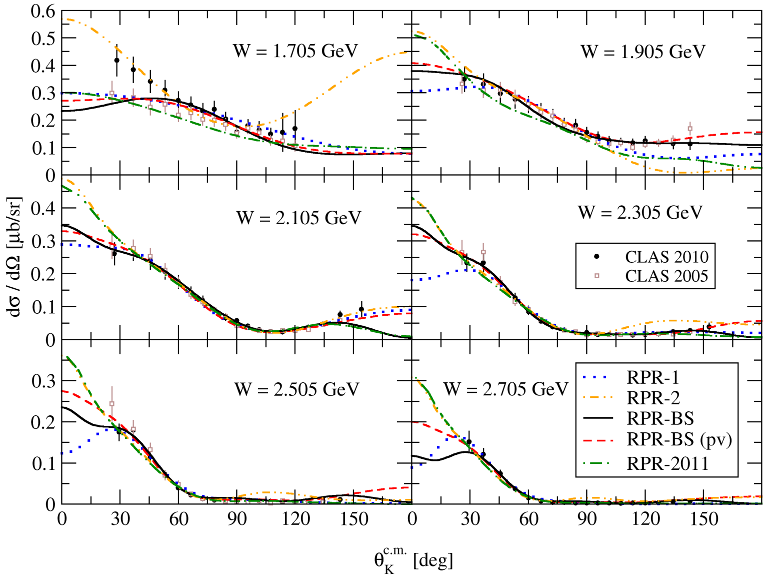
- only 3 parameters for $\mathcal{M}_{bgr}$ – fixed mainly by high-energy data (W>2.6 GeV)

Results with Regge-plus-resonance model

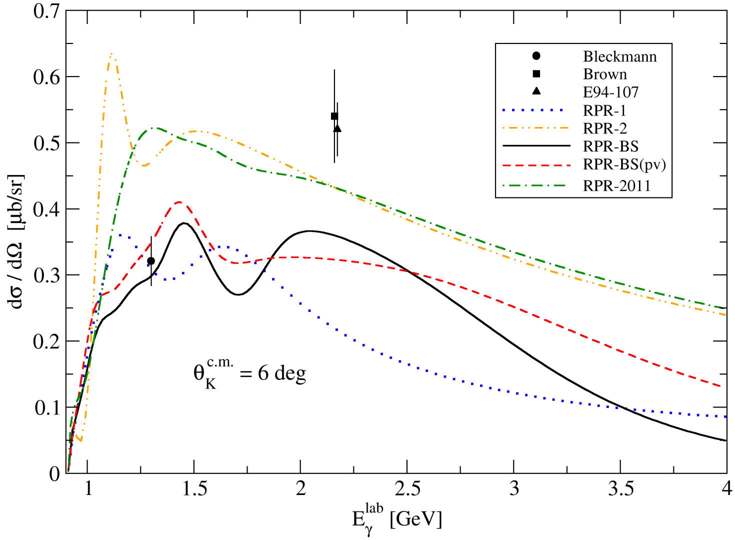
[P. Bydžovský and D. Skoupil, Phys. Rev. C 100, 035202 (2019)]



Results for photoproduction with RPR models



Results for photoproduction with RPR at small angles



Summary

- new isobar models BS1, BS2, and BS3 were constructed using a consistent description of the resonances with spin 3/2 and 5/2;
- $Y^*(3/2)$ resonances (not considered in older models, except for SLC) were found to play important role in description of the background part of amplitude;
- the selected set of N^* agrees well with that chosen in the Bayesian analysis with the Regge-plus-resonance model;
- we confirm importance of the missing resonances $P_{13}(1900)$ and $D_{13}(1875)$ for description of data in the $K^+\Lambda$ channel;
- new fits with the RPR model provide good description of data in the resonance region and above this region (CLAS 2010);
- predictions of the isobar and RPR models for the cross sections at small kaon angles differ – the data still cannot fully fix the models;
- the DWIA calculations of hypernucleus cross sections are sensitive to behaviour of the elementary amplitude at small θ_K and Q^2 close zero;

- the new DWIA calculations of the cross sections for electroproduction of ${}^{9}_{\Lambda}$Li, ${}^{12}_{\Lambda}$B, and ${}^{16}_{\Lambda}$N are in a reasonable agreement with experimental data from JLab [F.Garibaldi et al, Phys. Rev. C 99, 054309 (2019)];
- different isobar models for the elementary electroproduction, SLA and BS3, give similar results (30 – 40% difference);
- the calculations mostly underpredicts (by 10 – 60 %) the cross sections for ${}^{9}_{\Lambda}$Li and ${}^{12}_{\Lambda}$B (could be attributed to elementary production), however, they overpredict by 5 – 30 % the cross sections for ${}^{16}_{\Lambda}$N;

Outlook

- testing the isobar and Regge-plus-resonance models in the DWIA calculations (small θ_K) utilizing data on hypernucleus production;
- using the isobar model in photoproduction of K^0 on the neutron (deuteron data).

Thank you !