Report on the PhD dissertation "Electroproduction of Hypernuclei" of Daria Denisova (IPNP MFF UK and NPI CAS)

The thesis is devoted to the theoretical description of the electroproduction of Λ-hypernuclei, particularly to the reaction $e + A \rightarrow H + K^+ + e'$ when virtual photon, exchanged between initial electron and target nucleus A, causes the elementary process $\gamma_v + p \rightarrow K^+ + \Lambda$ on some proton of the target nucleus. The hyperon Λ, thus formed, lives long enough for the target nucleus A to form the Λ-hypernucleus H. The cross-section of this electroproduction of hypernuclei is determined by the distorted wave impulse approximation (DWIA) using different effective elementary Λ hyperon – nucleon interactions (elementary $\Lambda - p$ amplitudes) and different nuclear many body models for the structure of produced hypernucleus.

The main subject of this dissertation is the analysis of three effects that can influence the cross-section of the hypernucleus electroproduction, namely,

(i) The effect of the Fermi motion of protons in the target nucleus. Proton momentum $\vec{p}_p$ in the target nucleus is treated in three possibilities, $\vec{p}_p = 0$ ("frozen proton" approximation), $\vec{p}_p = \vec{p}_\Lambda + \vec{p}_K - \vec{p}_\gamma \approx \vec{p}_K - \vec{p}_\gamma$ ("frozen Λ" approximation), and $\vec{p}_p = \vec{p}_{opt}$ (optimum proton momentum approximation where the proton momentum $\vec{p}_p = \vec{p}_{opt}$ is determined by so called 2-body Hybrid scheme when the elementary amplitude is approximately on shell).

(ii) The effect connected with the kaon distortion. Usually, the wave function of the final kaon K^+ in the electroproduction process is approximated by plane wave. In the thesis the kaon wave function is determined by the more precise approach – distorted wave approximation determined by the optical model with the nuclear density participating in the kaon-nucleus optical potential.

(iii) The effect of the nuclear model used for the calculation of the single-particle transition density of the elementary process $\gamma_v + p \rightarrow K^+ + \Lambda$ involved in the hypernucleus electroproduction. Particularly, in the dissertation two nuclear models were used – shell model and so-called HF+TD$_\Lambda$ model.

In the dissertation, all these effects are analyzed in detail in numerical calculations for selected isotopes ${}^{12}_{\Lambda}B$, ${}^{16}_{\Lambda}N$ and ${}^{40,48}_{\Lambda}K$.

The dissertation consists of 4 chapters. The introductory chapter of the dissertation involves an overview of current knowledge of models and experiments on photo- and electro-production of hypernuclei together with an overview of existing state of the issue. There is also a brief list of other hadron-induced reactions used to study hypernuclei.

The second chapter is devoted to the theoretical models for the determination of the hypernucleus electro-production cross-section. Main ingredients needed for a calculation of the cross-section are elementary $n - \Lambda$ amplitudes and corresponding one-body matrix elements of the transition $n \rightarrow \Lambda$ operator between the many-body wave functions of the target nucleus A and produced hypernucleus H.

In the third chapter, the results of numerical calculations of the differential cross-section for the lowest excitation states of the hypernucleus H depending on scattering angle θ_{Ke} , or on the angle $\theta_{p\Delta}$ (with $\vec{\Delta} = \vec{P}_{\gamma}$ - $\vec{P}_{K}$), or on the energy E_{γ} (for given angle θ_{Ke} and $\theta_{p\Delta}$ and for given excitation state of the hypernucleus H. A total number of 25 such dependences were analyzed in the third chapter leading to the conclusions presented in the fourth chapter.

In addition to these 4 chapters, the dissertation contains also 4 appendices for the derivation of the most important equations of the DWIA hypernucleus electroproduction $e + A \rightarrow H + K^{+} + e'$.

In my opinium, the main results can be summarized in the following points.

- In connection with the aim of the investigation the influence of the Fermi motion of protons in the target nucleus A and in the hypernucleus H in the electroproduction $(eA, e'HK^{+})$ a method was developed that enables determining the 2-component form of the amplitude of elementary process ($ep \rightarrow \gamma_{v} \rightarrow e'\Lambda K^{+}$) inside nuclear matter.
- The 2-component elementary amplitude was further incorporated within the DWIA into the calculation of cross-section of the nuclear electroproduction $(eA, e'HK^{+})$ of hyperon Λ^{0} (2-component CGLN elementary amplitude +DWIA approach).
- Developed CGLN amplitude + DWIA method was used for various efects in predicted cross-sections for electroproduction of a wide range of hypernuclei (specifically, ${}^{12}_{\Lambda}B$, ${}^{16}_{\Lambda}N$ and ${}^{40,48}_{\Lambda}K$). – effect of proton Fermi motion, effect of the distortion of final state kaon wave function, effect of using various form of the nuclear density calculated using different nuclear many-body models.
- Proton Fermi motion effect consists in the determination of the optimum proton momentum $\vec{p}_{opt}$ combining the energy conservation for the elementary process $\gamma_{v} + p \rightarrow K^{+} + \Lambda$ and the energy conservation for the many-body process $e + A \rightarrow H + K^{+} + e'$. Fermi motion effect vary in dependence on kinematics of elementary amplitude and are more noticeable at higher photon energies (above 2 GeV in the lab. frame). Besides, it is more pronounced for more modern elementary amplitude BS3 in the comparison with older Saclay-Lyon A. It was also shown that optimum proton momentum acquires values which are closer to mean momentum of the proton in the target nucleus.
- Optimum proton momentum depends also on the angle $\theta_{p\Delta}$ of proton momentum and the transfer momentum $\vec{\Delta} = \vec{P}_{\gamma}$ - $\vec{P}_{K}$ and on the linear momentum of the hyperon Λ . It was found that the reasonable optimal choice of the angle $\theta_{p\Delta}$ (giving the best agreement with the experimental data) correspond to the situation when proton moves opposite to the vector $\vec{\Delta}$ and the momentum of Λ is minimal. This choice with the optimum proton momentum and the on-shell elementary amplitude was denoted as the optimum on-shell approximation.
- The hypernucleus electroproduction cross-sections were determined for the lowest excited states in the produced hypernucleus. In the thesis, two models were used for the calculation of excited spectrum of the hypernucleus, namely the NΛ Hartree-Fock

+ Tamm-Dancoff model (NΛ TDA model) together with the One-Body density-matrix element shell model (OBDME shell model) of J. Millener (taken from the ref.[56]). The NΛ TDA model was developed from the standard nucleon TDA model by the inclusion of Λ – hyperon into the TDA phonon structure. It was found that the excitation spectra for $^{12}_{\Lambda}B$ calculated with the OBDME shell model are very similar to one obtained with the NΛ TDA model. For heavier isotopes, like $^{16}_{\Lambda}N$, the PBDME shell model describes experimental excitation spectrum very well and the excitation spectrum obtained with the NΛ TDA model is a little bit shifted to higher energies for some excitation states. However, the NΛ TDA model can be improved by taking into account of the interaction among the TDA phonons (so called TD multiphonon model). The advantage of the TDA multiphonon model for the calculation of the heavy hypernuclei lies in the possibility of taking into account the 3-body interaction which is impossible for shell model calculations because of their demand of huge configuration space.

The topic addressed in the dissertation is undoubtedly actual. This is evidenced, for example, by the fact that the results for $^{40,48}_{\Lambda}K$ are applied for the prediction of excitation spectra of medium-mass hypernuclei in an upgoing experiments at Jefferson Laboratory. The results presented in the dissertation have been published in two papers in the Phys.Rev. C (see refs. [4] and [5]) and presented at 3 international conferences MESON2021, MESON2022 and MESON2023.

From the formal side I have no critical comments. Maybe one, a reader who is not an expert in hypernuclei (like me) may have trouble reading the theoretical part of the thesis, which contains a lot of relations containing symbols that are only explained in the appendixes without any reference. However, this is only formal drawback. On the other hand, the theoretical part is exhausting and testifying to the author's broad knowledge of the issue.

I have two questions for the candidate.

(i) The derivation of the optimum proton momentum on-shell approximation (determination of $\vec{p}_{opt}$) is based on the combination of the energy preservations for the elementary and the nuclear many-body electroproductions of hyperon in produced hypernucleus. However, it does not give sufficient number of conditions for the unambiguous determination of linear momenta and energies of all virtual and real particles participating in the process of the electroproduction. Important role is played also by kinematics of the electroproduction process (see Figs. 4 and 5) where a lot of angles between linear momenta of different virtual and real particles in both elementary and many-body electroproduction processes, connected with the one photon exchange approximation, participate. These angles and momenta should be fixed in the calculation of the electroproduction cross-sections as is discussed in the thesis for p_{Λ} , E_{γ_v} , $\theta_{\Delta p}$. Are there any other angles or momenta whose values are necessary to fix in the calculation of electroproduction cross-sections? If yes, how they were fixed?

(ii) My second question is about the HF calculation of the one-particle wave functions of nucleons and $\Lambda -$ hyperon in the hypernucleus H . While the calculation of the structure of TD_{Λ} phonons is described in the thesis, the reader does not know much about the HF determination of the single-particle wave functions of the hyperon which are necessary for the subsequent TDA calculations. It would be good to comment shortly HF calculation for hypernucleus.

At the end of my report, I would like to state that the dissertation of Daria Denisova fulfills all demands required for the PhD dissertation and after a successful defense I recommend to award the title PhD to her.

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