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Recenzja rozprawy doktorskiej / Referee report of doctoral dissertation :

Udai Singh

Investigations of mechanisms of particle production in proton-induced nuclear spallation.

The doctoral thesis of Udai Singh is devoted to thorough studies of proton-induced nuclear spallation on the basis of production cross section of particles and isotopes. The studied reaction is of great interest for both fundamental physics and many applications. Among the others, the most apparent concerns construction and operation of spallation neutron sources. Moreover, knowledge on the spallation reaction is significant for numerous applications of this process, e.g., for nuclear waste "transmutation" or production of radioisotopes for medicine.

In the dissertation, several aspects of the spallation reaction are studied. The nuclear spallation is a sequence of reactions, usually divided into two stages: intranuclear cascade and emission from the equilibrated remnant. The excited remnant nucleus can evaporate particles, but also undergo fission or multifragmentation. Theoretical models of the two stages of the reaction have been described systematically and clearly in Chapter 2. The compendium can be handy for anyone starting research in this domain. The Author presents the main assumptions and parameters of the models and their applicability to the spallation in the relevant energy range.

Chapters 3-7 show the results of research conducted by Mr. Udai Singh. Technically, two types of tasks have been performed:

- determination of the differential production cross section for light particles through analysis of the HADES data;
- model analysis of several data sets, including quantitative comparisons with the state-of-the-art models of nuclear spallation.

One of the serious problems occurring in experimental studies of the spallation process relies on a wide range of masses of particles and isotopes to be detected in the exit channel and the necessity to cover large phase space regions. The data presented by Udai Singh originate from several separate experiments, each providing other pieces of information. The studies of the first, fast stage of reaction are based on the HADES data for $p+^{93}\text{Nb}$ reaction at 3.5 GeV. In this case, U. Singh performed the data analysis, described in detail in Chapter 3. He took great care to control all the cuts necessary to select events of interest and determine uncertainties due to background subtraction procedure. The most challenging part of the analysis relies on determining the efficiency and acceptance corrections, and the related uncertainties. To this purpose, the Author used dedicated Monte Carlo simulations with sophisticated generators. In addition, he checked the internal data consistency, e.g., by comparing results obtained for separate sectors of the detector. To this part, I have two questions:

- Why does efficiency-acceptance factor depend on multiplicity of simulated events, as shown in Fig.3.16?
- What is the reason for such a significant difference between HADES sectors as concerns the cross section values (Figs.3.21-3.22) ?

The double differential cross sections for producing light particles and ions have been determined in a wide kinematic region, providing a very rich database for testing theoretical models. The results have been cross-checked with other data sets for spallation reactions on similar targets and at similar beam energies.

In Chapter 4, U.Singh compares the obtained cross sections to the model predictions. The quantitative comparisons show the successes and deficiencies of the models. Only one of them, INCL++, is equipped with the surface coalescence mechanism permitting the light nuclear cluster formation. This was one of the premises of using this model combined with models of equilibrium emission in the further analysis. The necessity of introducing (or improving in the case of INCL++) a coalescence mechanism has been shown.

Chapters 5-7 focus on the next stages of the spallation: equilibrium and non-equilibrium emission. In his thesis, Mr. S.Udhai raised an important question about completeness of the description based on two stages: an intra-nuclear cascade and emission from an equilibrated remnant. For comparisons with the models, the existing database of spallation cross section for $^{136}\text{Xe}+p$ and $p+\text{Ag}$ reactions was used. The data have been compared to predictions of four state-of-the-art models of equilibrium emission. The quality of model description for broad spectrum of isotope masses have been analysed. Arguments on the importance of the non-equilibrium emission were provided by comparing the data with models supplemented with a phenomenological description of emission from moving sources. Significant dependence of relative contribution of non-equilibrium components on mass and isospin has been shown. In Chapter 7, the Odd-Even Staggering of cross section has been studied.

Chapter 8 contains explanatory summary of all the results and conclusions.

The information contained in the dissertation is rich and many-fold, yet presented in a very clear and systematic way. Editorial quality of the thesis is high: figures are clear and often self-explanatory, and text is practically free of misprints and language errors. I have found a few minor editing errors, like reference to Fig.1.1.3 in page 9 (should be Fig.1.1), or an ordinate described as „A” instead of „Z” in figure 5.4 (description in the caption is correct). I am surprised with differentiation in description of angles: $+0^\circ$ and -0° in figure 3.4. The term „more tangential” is also debatable, though comprehensible.

I have no significant remarks, but I have several questions meant to initiate discussion:

- The coalescence model applied in INCL++ has a feature described in point (v) in page 22: In case the cluster does not fulfill specific conditions, it cannot be emitted, but „the leading nucleon is probed for the emission”; this assumption seems unrealistic since the created and absorbed cluster should result in no emission at all. Are there any works aimed at improving this mechanism?
- The HADES data are compared to various models of intranuclear cascade. What about protons or other light particles emitted after the equilibrium had been reached? Is their contribution negligible?
- In Chapter 3, discussing figures 3.26 and 3.27, the Author mentions scaling of the cross section with the target mass; is it possible to construct a phenomenological scaling law

based on available data? Such a scaling formula could, in the future, help to cross-check between data sets and provide approximate isotope production rates.

Summarizing: In the Doctoral Dissertation of Udai Singh: *Investigations of mechanisms of particle production in proton-induced nuclear spallation*, important questions about spallation mechanism were addressed. New set of rich and precise data for light isotope and pion production was obtained, providing an insight into a first stage of spallation. Predictive power of the models of both reaction stages was tested and their deficiencies or problems have been shown and discussed. This has a two-fold significance: for understanding of the reaction mechanism and for applying the models in practice, e.g. for predicting the isotope production rate. I conclude that the presented dissertation meets the requirements expected for Ph.D. theses and I recommend admission of the Candidate to the subsequent stages of the procedure, including the public defense.

I evaluate the scientific quality of the presented research as superior. I fully agree with the conclusion presented in the last paragraph: „Provided here new experimental cross-sections of high quality and performed critical analysis of the predictive power of various theoretical models of nuclear spallation can be important contribution to the further extension of understanding of nuclear spallation physics.” Taking into account the scientific excellence of the research and importance of the subject, I recommend the dissertation for distinction.

Yours sincerely,



Elżbieta Stephan