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Referee report on the doctoral thesis of Mr Udai Singh,
Investigations of mechanisms of particle production in proton-induced nuclear spallation

Nuclear spallation reactions are induced when a projectile carrying a large energy impinges on a target, generating a series of reactions and a wide variety of reaction products. The study and understanding of such reactions has direct application to various fields like the nuclear waste processing, accelerator-driven spallation neutron sources, rare-isotope production, medical physics, etc. There is therefore a high-demand for data on quantities such as total and differential cross-section for the production of the various reaction products. Among those target/beam/energy combinations that are of interest for the above-mentioned studies, only a few can be studied experimentally. The theoretical description of these processes becomes then very important not only to understand the physical phenomenon, but also to provide predictions for the total and differential cross-sections for those reactions that are not experimentally studied. Validation of such theoretical models with experimental data becomes then an extremely important step. The majority of theoretical models most commonly employed in such studies describes the spallation reaction process as composed of two steps. In a first stage, which happens rapidly, an excited residual nucleus is produced in an excited state by intra-nuclear cascades of nucleon-nucleon and nucleon-pion collisions. At this stage nucleons, pions and light charged particles are emitted. The first step is followed by a slower second one. At this stage, the remnant excited nucleus de-excites by emission of nucleons, light charged particles and intermediate mass fragments. The most-widely adopted theoretical descriptions for the process follow this logic. Different models are usually used to describe the first and the second stage of a spallation reaction. In the work presented in his doctoral dissertation by Mr. Udai Singh, several models were considered and their prediction capabilities probed. In the field of spallation reactions physics, a variety of open questions exist, several of which are addressed in this thesis work.

The doctoral thesis of Mr U. Singh is composed of 143 pages subdivided into 8 chapters, an abstract and the bibliography. The flow of the discussion is organised as to follow the reaction process according to its natural order.

In chapter 1 an introduction on the topic of spallation reactions is given, together with a description of the motivations for such studies and a summary of the open questions in the field. The chapter is concluded by a clear summary of the organisation of the dissertation manuscript.

In chapter 2 the Author presents an exhaustive overview of the leading theoretical models that are most widely used to describe the two stages of spallation reactions. A particular attention is dedicated to the description of those models most relevant in the context of the dissertation, namely INCL++, UrQMD and GiBUU for the first stage and ABLA07, SMM, GEM2 and GEMINI++ for the second stage of the reaction.

Chapters 3 and 4 address the investigation of the first stage of spallation reaction. First data obtained from measurements performed with the HADES spectrometer for the p+Nb reaction at 3.5 GeV are analysed by the Author in order to determine the differential cross section for hydrogen, deuteron, tritium and charged pions. The HADES device and experiment, the data reduction methodology (including identification of the particles, background subtraction, efficiency and uncertainties estimate) and the validation of the methodology by comparison with literature stemming from previous HADES measurement are presented in chapter 3. The results for the differential cross-sections of the p+Nb at 3.5 GeV reaction are presented and compared to various theoretical model describing the first stage of the reaction. The results of these analysis show that the models considered offer comparable degree of accuracy in describing the first stage of the reaction for light-particle production. The author selects the INCL++ model as the model of choice for use as input generator for the analysis of the second stage of the reaction.

In chapter 5 the Author investigates the second stage of spallation reactions by comparing the predictions of microscopic models for the emission of intermediate mass fragments and heavy target residues, with experimental data for the ^{136}Xe+p reaction at 1 A·GeV obtained from literature. Isotopic cross-sections for atomic numbers ranging from 2 to 56 were analysed in the framework of two step models, with the first step of the reaction being simulated by means of the INCL++ models studied in Chapter 4. The excited heavy residue that is the product of the first step of the reaction is then investigated through four different theoretical models (ABLA07, GEMINI++, GEM2 and SMM), which predicting power is probed. Such analysis shows that the GEMINI++ model provided the best description of the experimental data over the whole range of atomic numbers.

In chapter 6 the Author presents an extension of his investigation of the spallation reaction mechanism to look at the non-equilibrium and equilibrium contributions to the total production cross-section for different isotopes. By supplementing the microscopic contributions in INCL++ and GEMINI++ with a phenomenological moving source contribution, he looks for a missing contribution to the processes and for understanding their nature and dependence on the A, Z and the third component of the isospin T_3. The cross-section dependence on the ratio of protons and neutrons in the emitted nucleus is analysed utilising literature data for the p+Ag reaction at 480 MeV, finding a remarkable dependence of the relative yields on the T_3 component of the isospin.

In chapter 7 the Author investigates a different aspect of the problem faced when describing theoretically spallation reactions, namely odd-even staggering of the total cross-section. Three theoretical models that describe the nucleus de-excitation (ABLA07, GEMINI++, SMM), coupled to INCL++ for the description of the first stage of the reaction, were considered in this study and their predictive power probed by comparing their predictions with literature data. The dependence on T_3 of the total cross-section variation for the fragment emission was used to this extent. The results show that all models seem to be unable to reproduce the experimental data, a sign that they all seem to neglect the phenomena responsible for the observed odd-even staggering effects.

In chapter 8 a concise and exhaustive summary of the thesis is given. The dissertation is completed by a rich bibliography. It is important to note that part of the work presented in his thesis by Mr Udai Singh has already been published in peer-review journals with Mr Singh as the main author.

I have some questions/comments about the work presented by Mr Singh in his doctoral dissertation that I would like to propose for discussion at the time of the thesis defence. My remarks do not influence the very good opinion I have of the work presented by Mr Singh in his thesis.

Chapter 3. It would be useful to have a summary, e.g. in the form of a table, with the components of the systematic uncertainty

In fig 4.1. the last sentence mentions a so-called "higher angle". What is meant with higher, i.e. higher than which value?

Formulae 4.1 and 4.2 are a bit confusing, since in both cases the A factor is defined. It is my understanding that these formulas are used not only for averaging over bins (or describing the A-factor for the given bin i) in the two dimensional histograms of θ versus Energy, but also later for averaging over the various isotopes of a given element.

There are some typing mistakes in the discussion on A-factors and their calculation that need clarification: at page 107 (section 5.2) formula 4.1 for the average is quoted in the text, while equation 4.2 for the individual isotope is quoted in the figure caption.

No unique naming is used for the models: the names GEM/GEM2 and GEMINI/GEMINI++ are used interchangeably throughout the manuscript.

At page 105, actinium (Ac) appears instead of silver (Ag).

In Figure 5.4, the Y-axis label shows A instead of Z

In section 7.1 at page 129: the quoted ^{56}Fe+p reaction at 1 A·GeV is ^{136}Xe+p from Ref. [89] or p+Ag from Ref. [29]?

As far as the editorial aspects of the dissertation are concerned, Mr Singh made adequate use of figures and tables. The figures are large and easy to read. An exception are red/magenta and orange markers/lines, which sometimes can be challenging to distinguish.

There are some typos and language imperfections, and often very long sentences. Nevertheless, I don't find it necessary to detail them, since they don't affect in my opinion the quality of the work.

Summarising, Mr Udai Singh presented a very interesting excursion through the various stages of nuclear spallation reactions. Starting from the experimental study of the p+Nb reaction at 3.5 GeV, he compared the results with predictions from the most widely-used models for the first stage of the reaction and identified the one, which gives the most reliable predictions. The output of the selected model, namely INCL++, was then used to provide input data for the models employed to describe the second phase of the spallation reaction. These models predicting power was verified by comparison with literature data and different aspects of the reaction were investigated, not only with respect to isotopic cross-sections determination. The analysis of the reaction mechanism was in fact extended to the study of non-equilibrium and equilibrium contributions to the total production cross-section for different isotopes and odd-even staggering of the total cross-section.

The doctoral thesis "Investigations of mechanisms of particle production in proton-induced nuclear spallation" presented by Mr Udai Singh fulfils the requirements for doctoral thesis and I therefore ask for admission of Mr Udai Singh to the next steps of the doctoral dissertation.

Chiara Mazzocchi