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Referee report on doctoral thesis
of Sahil Upadhyaya

"Systematic analysis of nuclear reactions with a neutron rich projectile on multiple targets at intermediate energies"

The doctoral dissertation of Mr Sahil Upadhyaya is devoted to the exploration of the isospin transport in heavy-ion collisions at intermediate energies. The ultimate goal of such studies is a test of the role of isospin degrees of freedom in the symmetry energy term of the nuclear equation of state. The undertaken studies contribute to the very broad field of exploration of nuclear matter at conditions far from its ground-state. They are of crucial importance for comprehension of the mechanical and thermodynamic properties of nuclear matter in the exotic states present during the evolution of the astrophysical objects. Among them, the phenomena related to the formation and static properties of neutron stars and core-collapse of supernovae are of great interest.

Mr Upadhyaya has analysed the data from collisions of the neutron rich projectile ^{48}Ca with three different targets (^{12}C, ^{27}Al and ^{40}Ca) and at two beam energies (40MeV/A and 25 MeV/A). This research is performed within the scientific program of the FAZIA Collaboration. The acceptance and the energy range of detection system have been selected in order to register the charged reaction products of the neutron-rich quasi-projectile origin.

The dissertation of Mr Sahil Upadhyaya consists of 6 chapters and extensive bibliography of the relevant scientific literature. Mr Upadhyaya is a co-author of 5 papers from this list. The thesis contains a lot of figures presenting the experimental results, outcomes of the model simulations, comparative plots and summary tables. Very helpful are the lists o tables and figures included at the beginning of the work. The dissertation is written clearly, in good language. The figures and the tables are in most cases carefully described and properly referenced in the text.

In the introduction a brief outline of the heavy-ion collision physics is given. A classification of various scenarios of the collision depending on the kinetic energy and impact parameter is provided. The importance of the mid-central collisions at the intermediate energies for the studies of symmetry energy term of the nuclear equation of state is explained. The interest on the observables related to the isospin transport during the collision as an indicators of the evolution of the proton-neutron asymmetry in the colliding system is emphasized.

Chapter 2 contains the description of the FAZIA-PRE experiment and the FAZIA detection methods. The detection blocks composed of triple-sandwich telescopes (Silicon–Silicon-CsI(Tl)) are capable of charged particle identification in the broad energy range. The efforts undertaken by FAZIA collaboration in order to optimize the detection performance are listed. Described are as well the methods of signal processing and particle identification. Both the ΔE-E and advanced pulse shape analysis are used in this respect. In effect the registered charged particles are identified in very broad range up to Z=55 with the mass identification for nuclei of Z up to 20. In the FAZIA experiment the process of data reduction, particle and background identification seems to be to great extent automatized. The whole data handling is performed with the use of a software called KaliVeda, developed for INDRA experiment and adopted by FAZIA collaboration. The capabilities of this toolkit are presented. Finally, Mr Upadhyaya presents the detection setup and provides convincing justification for selection of beam/target parameters in his experiment.

In chapter 3 Mr Sahil Upadhyaya explains his strategy of data analysis in order to derive information about the isospin transport and the neutron pre-equilibrium emission in the studied reactions. He confirms that the detection system with the forward angles restricted acceptance is sensitive mainly to products of quasi-projectile origin. Thus, the examination of reactions with neutron-rich beam of ^{48}Ca should indicate the effects related to the neutron excess in the quasi-projectile products of the collisions. Moreover, variation of the target masses and the beams energies provides him the possibility to control the reaction dynamics by observing behavior o simple and complex observables. He has decided that his method will consist in comparison of the shapes of obtained experimental distributions with respect to the target mass and with respect to the beam energy. He performs his comparisons for distributions of particle charge, Z, particle mass, A, and particle multiplicity, M. The same scheme of comparison is performed for isospin observables. The distributions of <N>/Z as a function of fragment charge, Z, and the <N>/Z on dependence of a longitudinal velocity of fragment, $v_{\parallel}$, are used in this respect. The sensitivity of the isospin variables to the observed velocities of light fragments is explained.

In the following the Author has performed more detailed analysis of the longitudinal velocity distributions of light fragment with respect to their <N>/Z. Considering velocities of these particles in the Quasi Projectile reference frame he identified the backward and forward emitted fragments. The dominance of backward emission of light fragments with $Z \leq 7$ and <N>/Z > 1 indicates their origin from neutron enriched region of the projectile-target overlap in peripheral collision, called a “neck”. This effect is present in data collected for both beam energies and for all three targets. Its strength varies consistently with expectations due to the target mass and beam energy.

Mr Upadhyaya has noticed as well that the <N>/Z vs. Z distribution decreases when the beam energy increases. He interprets this fact as an evidence of coherent sum of two complementary processes: (i) an increase of pre-quilibrium emission probability for higher beam energies; (ii) an increase of excitation and multi-fragmentation probability of the system when projectile energy increases. In both cases a faster balancing of neutron/proton ratio takes place and average N/Z of emitted fragments must decrease.

Interpretation of very complicated processes as those explored in the thesis of Mr Upadhyaya demands a support from the simulations with the use of reliable theoretical model. Mr Upadhyaya performed simulations of the collision process with the HIPSE model whereas the contribution from the de-excitation processes were simulated with two other models, namely the SIMON and the GEMINI++. Results of these simulations are shown in chapter 4. All three models are briefly presented. The parameters of the models selected for simulations of the reactions of interest were adopted from literature. Mr Upadhyaya has created the theoretical 4π products distributions for the reactions studied in his work and applied on them the experimental constrains. He has obtained the distributions of the simple- and isospin sensitive observables – the same as for his analysis of experimental data. Each theoretical distribution was modeled in two versions: first, when the HIPSE model has been combined with the SIMON model, and the second, when de-excitation phase for HIPSE products was calculated by the GEMINI++ code. The model distributions of Z, A and M for HIPSE+SIMON and HIPSE+GEMINI++ are similar. However, the distributions of <N>/Z, which are sensitive to isospin dynamics, visibly differ for both options.

In chapter 5 the Author has performed the detailed comparison of experimental and theoretical results. Significant number of comparative plots of distributions as well as the ratio plots are included. In general the discrepancies in the model/data comparison for simple quantities as Z, A and M varies within a factor ±2. Unfortunately, the quality of the data description by both optional simulations changes incoherently from target to target, for different beam energies and along the domain of examined observable (A, Z, M, $v_{||}$). Thus, it is not possible to judge in favor of one of the model combinations. Mr Upadhyaya compared also the averaged values of simulated and measured observables. In this case the discrepancies are smaller but still significant. Mr Upadhyaya could not avoid the correct and jutified conclusion that the "quantitative description of the nuclear reactions by HIPSE is not in a complete agreement with experimental data".

For the isospin dependent distributions of <N>/Z vs. Z and <N>/Z vs. $v_{||}$ the theoretical curves also miss the experimental ones in rather incoherent way. But here the Author is more satisfied and classifies this situation as a reasonable agreement of the data and the model. Astonishingly, the both optional simulations provided a good agreement with the data for <N>/Z values around the $v_{||} = v_{Beam}$. But for other specific distributions, which show the possible component of light fragment emission from the neutron rich region of a neck, only the HIPSE+SIMON has provided the result similar to the experimental values. This finding is rather confusing and confirms that at the current stage of the model development its predictive power is not sufficient to support the interpretation of experimental data presented in this dissertation.

The thesis of Mr Sahil Upadhyaya makes a very good impression. It comprises a lot of new experimental results and their interpretations. The predictive power of combinations of three theoretical models of nuclear collision and de-excitation have been tested as well. In this case the limitations of the models are indicated.

What is missing in the thesis, is the more detailed information about the data selection methods and possible sources and magnitudes of uncertainties. The problem of uncertainties is not addressed at all and the reader has to assume that they are negligible.

It would be as well desirable to know if any information about the energy- and angular distributions of the reaction products can be obtained and utilized for identification of specific processes in the future analysis of FAZIA-PRE data.

A few typos in the text of the thesis are noticed. In the important figure no 3.7, unfortunately, the horizontal axis with a longitudinal velocity is mistakenly labeled as an atomic number Z.

The indicated above shortcomings of the thesis do not change a very positive opinion about the work done by Mr Sahil Upadhyaya.

Evaluation of PhD Candidate and his research work

My assessment of Mr Sahil Upadhyaya as a PhD Candidate is positive. He actively participated in the work of FAZIA Collaboration working on the optimization of readout electronics, taking part in the measurements and conducting the data analysis. He performed as well the simulations of the studied reactions with the use of combination of three theoretical models. Mr Upadhyaya presented his results in 6 conferences and workshops. He is co-author of 12 scientific publication. His dissertation is of significant scientific value. Particularly, the advantages of his thesis are as follows:

1) the difficult but important subject of examination, namely the properties of nuclear matter at exotic conditions typical for heavy ion reaction at intermediate energies has been undertaken;

2) significant number of new valuable experimental distribution of A, Z, M, $v_{\parallel}$, N, N/Z, <N>/Z for two beam energies and three combination of projectile-target nuclei is obtained;

3) experimental distributions are confronted with theoretical ones. The latter were obtained by means of simulations with the use of the HIPSE+SIMON and the HIPSE+GEMINI++ models. The discrepancies are described;

4) obtained experimental distributions will be an important benchmarks for development of theoretical models;

5) convincing arguments in favor of isospin drift effect visible in the FAZIA-PRE data are presented;

6) the increase of N/Z equilibration rate with the beam energy due to increase of pre-equilibrium emission and multi-fragmentation of the system is shown.

I confirm that Mr Sahil Upadhyaya satisfies the formal requirements for doctoral candidates according to the appropriate Polish regulations (*Ustawa - Prawo o szkolnictwie wyższym i nauce (t.j. Dz. U. z 2020 r. poz. 85 z późn. zm.)*).

I recommend admission of Mr Sahil Upadhyaya for the subsequent stages of the procedure, including the public defense.

Krzysztof Pysz