Report on doctoral thesis of Mr. Sahil Upadhyaya
“Systematic analysis of nuclear reactions with a neutron rich projectile on multiple targets at intermediate energies”

The submitted here doctoral thesis of Mr. Sahil Upadhyay consists of 6 main chapters, of which chapter 1 entitled „General introduction” gives general and standard information about collisions of nuclei. In chapter 2 we find out usefull details about the FAZIA set of detectors and the experimental setup used in FAZIA-PRE experiment, carried out in 2018 in LNS-INFN in Catania which is the subject of discussions within this work.

In this document presenting an analysis of part of the results of this experiment, the dependence of the distributions of particles and nuclear clusters emitted by reactions in the medium energy range (25-40 MeV/A) for three target nuclei (12C, 27Al, 40Ca) and one neutron-rich 48Ca projectile on the mass, charge and multiplicity of emitted particles is discussed, as well as isospin effects expressed by the dependence on <N>/Z, where <N> is the averaged number of neutrons over all detected decay fragments with a given number of protons, Z.
The author additionally considers these distributions also as a function of the mass of the target nucleus using various permissible projectile-target combinations. In the experiment, the target and projectile nuclei were used, which are isospin-symmetric (N/Z~1) as well as isospin-asymmetric (N/Z~1.3-1.4). This allows to study the influence of isospin degrees of freedom on the distributions of registered particles and, consequently, emissions from the so-called neck region. Although the PhD student mentioned in the introduction that this research will be important from the point of view of the influence on symmetry energies, no reference to this issue can be found in the conclusions.

In Chapter 3, the PhD student presents, analyses and gives interpretations of the physical effects observed in the experiment that accompany the reactions studied. He divides the data into 2 groups: the first one, relating to basic observables, i.e. distributions of fragments with respect to the charge Z, mass A and their multiplicities M, and the second part concerns the already mentioned isospin relations, which are currently in the centre of interest of medium energy nuclear physics.

In my opinion, the presentation of the results is carried out in a logical clear and clever manner in the form of accurately described graphs, maps and clear tables. Additionally, the author quotes standard as well as hypothetical arguments explaining the observed effects. In the vast majority these arguments are correct and sufficient.
In chapters 4 and 5 the author presents a comparison of obtained results with simulations of the course of the considered reactions with the help of the system of coupled HIPSE+SIMON and HIPSE+GEMINI++ codes, used by experimentalists in this field, describing the evolution of the reaction, the formation of QP, QT and CN nuclei and their possible further decays depending on the excitation energy and other factors. It should be strongly emphasized that the models underlying these codes are purely phenomenological, not taking into account the full richness of nucleon and cluster interactions nor complicated dynamics of interacting many-body systems (as e.g. in the Quantum Molecular Dynamics model and its various variants). It is based on the phenomenological interaction potential of spherical target and projectile ions, which shape is controlled by a single parameter \alpha_a.
The parameters of this model, fitted to several reference reactions, are considered to be, to a first approximation, independent of the energy and the reaction substrates. Additionally, the initial FAZIA-PRE experiment included a detector system covering only a small part of the full solid angle, which prevented detection of particles scattered in all possible directions, e.g. QT nuclei, which due to the reaction conditions were scattered in directions transverse to the beam. In order to make such a comparison possible, the author used a data filter available in HIPSE, which tries to take into account these limitations. In the end, the comparisons presented between experimental and simulation data are not fully conclusive either about the quality of the analysis of these experimental data or about possible deficiencies in the HIPSE program.

The presented comparisons of the averaged quantities <Z>, <A>, <M>, <N/Z> presented especially in Table 5.1 page 84 seem to be very good in the context of these limitations, although the author himself emphasised that very good agreement occurs only for some of the observables marked in bold.
It is to be appreciated that the PhD student, as an experimentalist, was tempted to make such a comparison thus proving his skill with these complex theoretical tools and understanding their limitations. The

conclusions of these comparisons, I believe, have further helped in understanding the effects affecting the behaviour of the fragment distributions under study.
In the last chapter 6, the author brings together in brief points all the main conclusions of the detailed discussions in the previous chapters.
The PhD student realizes that the experiment discussed here was a preliminary test of the capabilities of the FAZIA system, which in addition was used here in a rather truncated form. However, he notes unique abilities of this apparatus to detect the electric charge of particles and their energies and, in addition to typical correlations for standard observables in intermediate energy reactions, he attempts to study the currently important problem of the so called "isospin drift" effects and emission of light particles and clusters from the neck region. He uses, however, here a simplified reasoning taken from the work [9], which he does not cite exactly in the paper, but only points to its general characteristics, which enable a rough identification of fragments from the neck region and peripheries of the QT and QP nuclei. He also points out, that even in the topic of so far typical distributions of particles in the Z and A function, one observes some subtle dependence from mass of the target nucleus, not reported so far in theoretical works and not totally correctly reproduced in HIPSE simulations.

In his work, the PhD student cites more than 100 pieces of literature, mostly from leading international journals. He himself is the author of 12 co-authored publications in renowned world journals.

In spite of few remarks on the legibility of some graphs and requests for clarification of selected issues, I highly evaluate the dissertation of Mr. S. Upadhyaya in terms of its content and editing, and I believe that it fully deserves to be admitted to public defense.

Despite this positive impression, however, I would like to ask the author a few questions to clarify certain issues.

Page 42, top:
„Unlike the observations in [94], where no significant difference in the <N>/Z of the fragment was seen w.r.t. target mass, in FAZIA-PRE data, target dependence was observed, because targets under consideration were almost N/Z symmetric. So the detected QP fragments should show the effect of changing target mass on N/Z. The main outcome here is that the fragment <N>/Z decreases with increasing target mass……"
„This could be correlated to the fact that total N/Z of the system decreases with increasing target mass. A simple reason being that for smaller target mass, there are less target nucleons to interact with which can easily be exchanged in the interaction. On increasing the target mass, the number of target nucleons increases and also the elastic scattering of the projectile increases due to increase in the grazing angle. So the nucleon exchange becomes difficult."

1) The sequence of statements above seems to be very general and thus not fully convincing to justify without any doubt the effect of changes in <N>/Z distributions as a function of the mass of the target nucleus, given that it was not reported in the cited paper, nor is it even qualitatively correctly reproduced in the presented simulations.
Of course, the above cannot be a reason to doubt its occurrence and therefore should be investigated more in details in the future.
Admittedly, the first and in my opinion the strongest argument that "total N/Z of the system decreases with increasing target mass" would explain this dependence in general, but further arguments are too superficial. It would therefore be good to analyse in more depth how the number of interacting nucleons and the simultaneous increase of the grazing angle generates this effect.

2) In Figure 3.7, the horizontal axis should be described by v_{ll} rather than Z.

3) Is it possible to distinguish a kind of „the most like" direction of the emitted particles from the neutron enriched neck? Is it so that particles from the neck are emitted **mostly** transversely to the beam direction, or this assumption is rather not justified?
If such a statement would be true, is it possible to measure them in the FAZIA-PRE experiment, where the forward angles to be accepted are (hardly) between 2-16 degrees?

What the comparison with the HIPSE simulations is concerned:

4) What is the purpose of performing very detailed comparisons between experimental data and simulations within the HIPSE framework, especially in the case of rather poor acceptance of forward angles of this experiment?
5) Is it possible to say anything general about deficiencies of the HIPSE code which lead to not satisfactory quantitative accordance with experimental data? In particular,
* what about the deformation properties of colliding elements in the entrance channel?
* may the outcome of this experiment be used in the future to „calibrate" the three
(x_tr, x_coll, \alpha_a) parameters or e.g., due to small acceptance angles of detectors this data are rather useless?

6) Has it been studied the sensitivity of the simulations on tiny variations of these parameters (or some subset of them) around their fixed values, at least, in one or two cases?
Such an investigation is often used in order to make sure that the simulations produce stable results against changing their parameters, which are, to some extent, arbitrary. Of course I realize that it might be meaningless, especially when using filtered data and if such studies are already performed and published.

7) Concluding this part, since it couldn't be easily found in the text, let us ask the author what is, **in general**, the „added value" of preforming these comparisons with the HIPSE system? Is this comparison really enriched one's understanding of here investigated physics?

Page 47 after Fig. 3.11:
„...The Delta(N)/Z for fragments with Z~7-15 almost approaches zero. This is visible due to the effect of isospin diffusion, that should affect all the BWD and and FWD fragments in the same ways, gets canceled out".

Is this conclusion based on some simplistic picture that the isospin currents passing through the neck (blue) zone (see Fig. 3.8) from the QT towards QP and the opposite one just mutually cancel out?

Further on:
„This suggests that the positive value of Delta(N)/Z for ***lighter fragments*** *due to the high <N>/Z of the fragments coming from neutron enriched neck.*
This confirms the effects of isospin drift. The negative Delta(N)/Z for 25 MeV/A system in Fig.3.12(a) is related to the fact that the <N>/Z of FWD fragments is high due to the elastic scattering events leading to detection of a neutron rich PLT…."

Does it mean that more FWD fragments as compared to the BWD ones are detected? Can it be the effect of relatively low FWD detecting angles limited by the imposed geometry of the experimental setup?
Are you expecting a similar as above isospin effects for \Delta(N)/Z when using full 4pi detector geometry?

Page 69, par. 1
"...But around projectile Z, the trends become opposite. In comparison to trends from the experimental data, the target dependence observed in HIPSE for Z distributions is similar for Z>=7"

Does the above statement mean that the emissions from the neck region are not (well) reproduced by HIPSE simulations?
Can it be, among other things, the effect of neck shape which can not be controlled in the HIPSE code and therefore only collisions of spherical nuclei are there considered?

In conclusion, in my opinion, the presented doctoral dissertation of Mr. S. Upadhyaya due to the contents, results and discussions presented in it with high scientific level and significant contribution to the state of the art in the field of medium energy nuclear reactions, fully deserves to be admitted to public defense.

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