NEW PERSPECTIVES FOR STUDIES OF REACTION MECHANISMS AT LOW-MEDIUM ENERGIES*

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Many open questions regarding the study of reaction mechanisms with heavy ions have still to be solved, even in the energetic range between 5 and 20 MeV$/u$, which is covered by the accelerating system Tandem XTU–Linac ALPI of the Laboratori Nazionali of Legnaro. Using complex apparatuses like GARFIELD, coupled with different ancillary detectors, it is possible to perform exclusive measurements, which should be capable of giving new important information, in order to better understand both nuclear structure problems, like for example the study of the mechanisms underlying the Giant Dipole Resonance Damping, and reaction mechanisms phenomena, like the characterization of those mechanisms which are responsible for the many-fragment emission. Preliminary results and future plans to be performed with the GARFIELD facility have been described.

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1. Introduction

The energy range covered by the complex Linac ALPI–Tandem XTU of the Laboratori Nazionali di Legnaro, between 5 and 20 MeV/u, has already been studied in the past, but most of the performed measurements were inclusive and incomplete. This was expecially due to the limited detection efficiencies of the experimental apparatuses (often only discrete elements covering small solid angle portions have been used). Several questions are therefore still open and require an ambitious experimental program to be performed. In order to go further with the knowledge both on nuclear matter behaviour in critical situations as far as we deal with density or temperature, and on those problems more directly connected to nuclear structure, coincidence measurements and correlations studies between key observables become necessary.

2. Experimental set-up

The GARFIELD apparatus is a large acceptance detector, composed of three parts, which finally cover almost the whole solid angle. Two cylindrical drift chambers with gaseous micro-strip detectors in the amplification region cover the region between $\theta = 30°$ and $150°$: the ΔE signals are provided by the microstrip gas detectors, which collect and pre-amplify the electrons produced in the gas along the track of the reaction products, while the residual energy signal is given by CsI(Tl) crystals, which are located in the same gas volume.

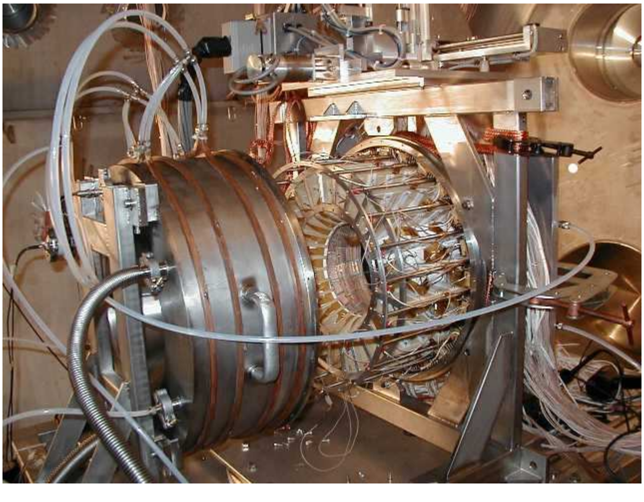

Fig. 1. Picture of one of the two drift chambers of GARFIELD.

The two drift chambers are divided respectively in 21 and 24 sectors: a picture of one drift chamber is shown in Fig. 1. The forward angles can be covered by different detectors such as position sensitive parallel plate avalanche counters (PSPPACs — 20×20 cm^2), followed by some Si(Li) detectors, in order to measure energy and mass of the forward products using the Time of Flight — Residual Energy method. In alternative an annular three stage telescope can be used ($6^\circ \leq \theta_{\rm lab} \leq 18^\circ$), which is composed by 8 ionization chambers, a silicon detector 300 μm thick, divided in 8 sectors of 8 strips each, followed by 16 CsI(Tl) crystals. This so-called Ring Counter can identify a broad range of products, from light charged particles to heavy residues with a low identification threshold (< 800 keV$/n$).

There are many interesting and still puzzling themes to be investigated in this field. We have addressed our effort and we will dedicate our activity to the following problematics:

- Cross section measurements relevant for radiotherapy and for the evaluation of the Health Risk for Astronauts;
- The study of the damping mechanisms of the giant dipole resonance in highly excited nuclei, coupling GARFIELD [1] with the HECTOR Array [2], which is made of 8 BaF_2;
- The study of thermodynamics and dynamics in nuclear physics: searching for possible signatures of a critical behaviour of nuclear matter starting from relatively low energy;
- The study of the open questions in dissipative processes: energy partition depending on the mass asymmetry of the exit channel, limit of the Nuclear Exchange Model for bombarding energies greater than 10 MeV$/u$, new dynamical processes as for example the random neck rupture or the cluster exchange.

3. Cross section measurements relevant for radiotherapy and for the evaluation of the health risk for astronauts

The use of carbon beams is nowadays considered very important for the high ionization density induced by these ions at the end of the range and for their high biological effectiveness [3]. This permits to use very focalized doses on the tumoral mass. Nevertheless, more information is needed on nuclear cross sections of carbon on tissue — equivalent materials.

The optimization of the treatment with a Heavy Ion Induced Therapy to maximize the Tumor Control Probability can be improved in order to control the Risk of Complications in Normal Tissues, which could be caused essentially by lighter particles with different range and stopping power, produced for example from the break up of the primary beam. Cross section data are therefore requested to implement codes which should predict the biological effects of carbon beams and of their secondary products in a broad energetic range [4]. Measurements have been performed in Legnaro studying the reactions ^{12}C on ^{12}C, ^{40}Ca, Mylar,^{181}Ta from 6 to 20 MeV$/u$ and ^{16}O on ^{12}C, from 6 to 18.5 MeV$/u$.

3.1. Preliminary results

Some preliminary results obtained for α-particles emitted in the reactions $^{12}\mathrm{C}+^{12}\mathrm{C}$ and $^{16}\mathrm{O}+^{12}\mathrm{C}$ for 4 different angles are shown in Fig. 2 as a function of the incident energy. Double differential cross section spectra $\frac{\delta\sigma^2}{\delta\Omega\delta E}$ for the two reactions and as a function of the different incident energies have also been obtained.

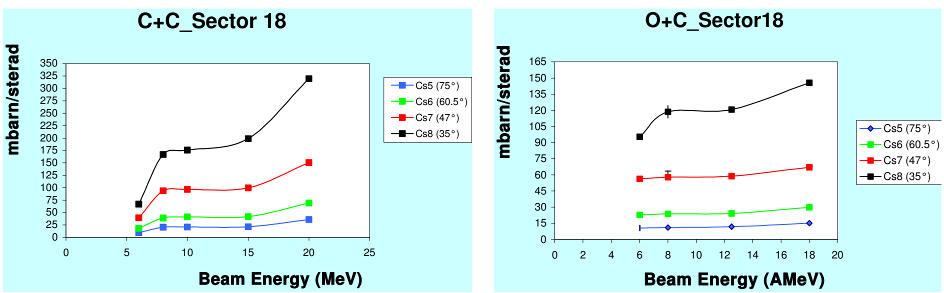

Fig. 2. Cross section for α-particles emitted in the C + C reaction (left panel) and O + C reaction (right panel) for different detection angles, as a function of the incident energy

The analysis is still in progress: much work has to be performed getting cross section information for α-particles for all the other targets, but also for different reaction products which have to be studied in order to give information on the total reaction cross section.

4. Studying the damping mechanism of the giant dipole resonance at high excitation energy

The relatively high excitation energy region ($\epsilon^* > 2$ MeV, that means high temperature values) is still not well understood as far as it regards the problem of the damping mechanism of the Giant Dipole Resonance built on excited states [5]. The old open question, whether the width of the GDR saturates or increases, has now addressed the fact that the excitation energy of the emitting system is not really well determined.

All the measurements performed up to now were essentially inclusive. This is a good approximation at low energy, where the fusion-evaporation channel accounts for the major part of the reaction cross section. At higher energy this is no more the case: it becomes therefore necessary to perform further measurements as exclusive as possible. As a first the group in Seattle [6] studied the reactions ^{18}O + ^{100}Mo at 250 MeV, measuring the light charged particles emitted when a tag on the γ-rays was given (that is $E_\gamma > 10$ MeV). Following that idea, we decided to measure in the same time the coincidences between Evaporation Residues (ER) and the high energy γ-rays, using two different reactions with different asymmetry in the entrance channel: ^{64}Ni + ^{68}Zn at 400 and 500 MeV incident energy, corresponding to 150 and 200 MeV of nominal excitation energy respectively and ^{16}O + ^{116}Sn at $E_{\rm beam} = 250$ MeV (with $E^* = 200$ MeV). In the same time and using the same experimental constraint on the ER trigger, we performed a coincidence measurement between the ER and the light charged particles. Triple coincidences were also collected, but of course they are limited by the efficiency of the whole coincidence system. From a moving source fit method the fast and evaporative components of the light charged particles spectra can be extracted, leading to an estimation of the pre-equilibrium emission.

4.1. Preliminary results

Already very preliminary results [7], suggest that interesting information, can be derived from these very clean measurements. The γ-ray spectra for the three reactions are shown in Fig. 3. The two spectra associated with the measurements with the Ni beam at two different bombarding energies, are very similar. On the contrary, the γ-ray spectra for the two reactions which should lead to a compound nucleus at the same nominal excitation energy (made through the symmetric (Ni + Zn) or asymmetric (O + Sn) entrance channels) differ in their statistical part.

Calibration of the energy spectra of the light charged particles is in progress in order to get the information on the amount of pre-equilibrium emission in the two cases. From a direct comparison of the particle spectra in the same detector at relatively forward angles (30°–40°) important differences seem to be already visible from the raw data. The analysis is in progress regarding both, the calibration of the Garfield array and a more refined study of γ-rays spectra.

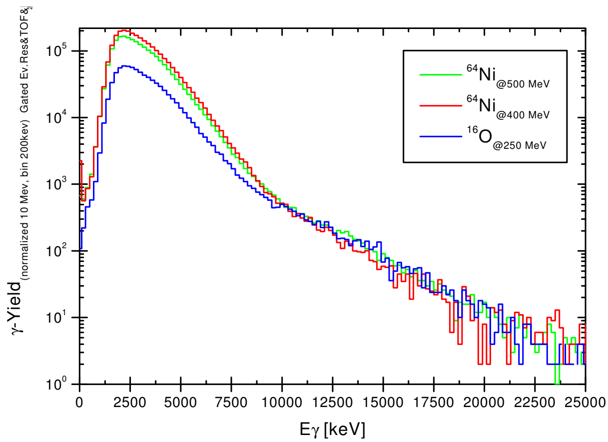

Fig. 3. Comparison between γ-rays spectra obtained from the reactions ^{64}Ni + ^{68}Zn at 500 MeV, ^{64}Ni + ^{68}Zn at 400 MeV, ^{16}O + ^{116}S at 250 MeV.

5. Multifragment emission

The multi-fragment emission is an important phenomenon which made the scientific community of intermediate energy regime debate since many years. Initially the production thresholds for such a phenomenon was in fact expected at energies comparable at least to the Fermi energy regime, that is around 40–50 MeV/u, but lately the production threshold seemed to be lowering more and more. The main debate in the past was based on the question whether the emission of many fragments was a fast (almost prompt) process or a sequential one (subsequent sequential fissions). Nowadays the debate is more centered on the problem whether the mechanism of multifragmentation is purely statistical (the emitting system is equilibrated) or wether it is governed by dynamical forces. In spitte of the fact that these two cases are characterized by different scenarios, often the same experimental signatures may be expected. It is then of great importance to decide on which measurements and what kind of data analysis should be performed to shed more light on the studied phenomena. On one side, in fact, the behavior of the system can be associated with a critical behavior of the nuclear matter where some experimental signature can be observed as a proof of a phase transition (continuous or discontinuous is another matter of debate). On the other side important ideas on dynamical driven instabilities like surface or volume instabilities are considered and can be used to describe the system as it was in a continuous evolution from a compression stage to an expansion state, but never reaching the thermo-dynamical equilibrium. Some statistical microcanonical calculations have been performed considering an equilibrated system and the models predict, for finite and isolated systems, anomalies [8] of the thermo-statistical observable at the onset of multi-fragment production. These signals, corresponding to the opening of the phase space and to the increase of the variances of the static observable, are expected already at an excitation energy of 2–3 MeV for a first order phase transition. The caloric curve, which relates the internal energy of an excited system at thermodynamical equilibrium to its temperature, should be *a priori* the simplest experimental tool for the existence of a phase transition. A back-bending in the caloric curve corresponds to the increased request of energy necessary to create fragments and to the consequent decrease of the available thermal energy and it would be a strong indication of a possible transition of first order. Other signals are expected, which can better determine what is going on, and must be cross checked because no signal by itself is sufficient to demonstrate the phenomenon.

For example if a back-bending is observed a negative branch in the heat capacity should also be present in correspondence to critical events to signal the formation of latent heat [9]. From the experimental point of view, apart from looking at the major number of possible signals (see for example the scaling laws which relate the behavior of observables at different scales, that is for different sizes of the system) a great accuracy is requested in the measurements.

Pushed by the theoretical predictions and also by the fact that at relatively low energy the experimental situation could be more easy to face, due to the lower number of unknown phenomena, we planned an experimental program to study emission of many fragments at low energy, hoping to contribute to shedding light on the nuclear matter behavior.

5.1. Preliminary results

A first measurement has been performed studying the reaction 11 MeV/u of ^{32}S on ^{58}Ni at the Laboratori Nazionali di Legnaro. A variety of different models, from statistical sequential models (GEMINI) [10] to statistical multifragmentation models (SMM) [11] and to dynamical models (CMD, QMD) [12], could often describe the inclusive distributions resulting from experiments with many fragment production. Again only very exclusive analyses could permit to shed some light on the equilibration reached by the systems, on the collective degrees of freedom still playing a role or on whatever else can influence the system under study.

It becomes therefore really important, besides filtering correctly the simulated events through the experimental acceptance of the apparatus, to look for those correlated observables which can help in discriminating between different hypothesis.

For example the charge correlations between the three largest fragments in one event permit a first characterization of the kind of charge partition and of the major production mechanism. Then of course relative velocity correlations can give some insight on the emission time between following steps *etc.* A dynamical code simulation has been performed and filtered through the experimental apparatus acceptance. Selecting three fragments in the whole apparatus a remembrance of the entrance channel is present, so this means that even large impact parameters are still included with the projectile-like fragments (PLF) visible in the spectrum. When the selection is made on events with three fragments detected at large angles that is from 50° to 130° in the center of mass reference frame, only central collisions are selected.

The experimental Z distribution as detected in the whole apparatus and that one detected only in GARFIELD are shown together with the same distributions simulated by CMD in Fig. 4.

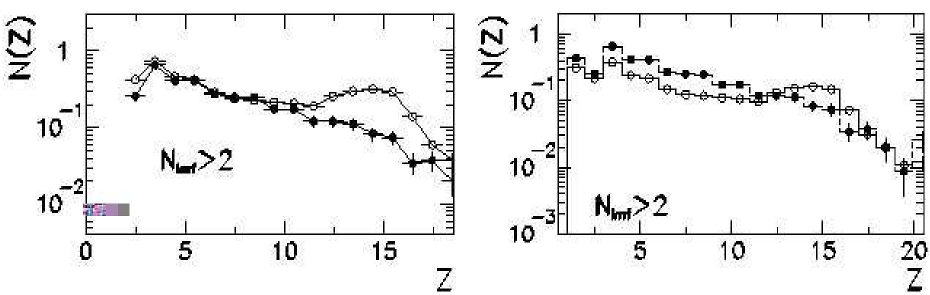

Fig. 4. Left panel: Experimental charge distribution of IMF detected in the whole apparatus (open symbols) and in GARFIELD (full symbols) for events with at least three fragments; right panel: Charge distribution of 3 fragments predicted by CMD emitted everywhere in the apparatus (open symbols) and detected in GARFIELD (full symbols), which correspond to $b < 2.5$ fm.

The bump close to $Z = 16$ shows the PLF - this bump completely disappears in the GARFIELD-only distributions. The correlation function of α-particles, studied for events where the two α's were emitted together with three fragments detected in GARFIELD, confirms again that, when the three fragments are detected in GARFIELD, they are associated with central events — they are correlated with an isotropic emission of α-particles.

The correlation between the charge distributions of the three largest fragments in the event (Dalitz plots) are shown in Fig. 5 and 6: For the GEMINI case, the filter applied includes the whole apparatus and the simulation regards the case with an angular momentum close to the maximum L for that reactions ($\langle L \rangle = 48\hbar$), because only in this case the sequential statistical model predicts emission of Intermediate Mass Fragments. It is quite

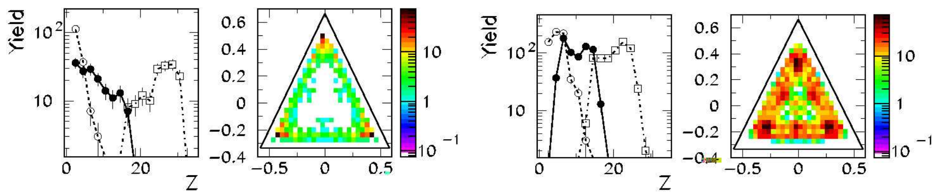

Fig. 5. Charge distribution of the three largest fragments detected in each event and relative Dalitz plot simulated by GEMINI statistical model with $\langle L \rangle = 48\hbar$ (left panel) and the same, but simulated by SMM statistical multifragmentation model (right panel).

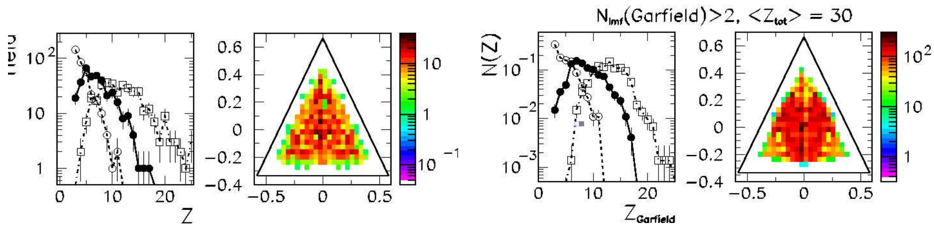

Fig. 6. Charge distribution of the three largest fragments detected in each event and relative Dalitz plot simulated by CMD dynamical model (left panel) and the same, but for experimental data (right panel).

obvious that due to the very asymmetric partitioning of the fragments, as predicted by the sequential code, this is automatically cut out from the comparison with the experimental distribution, because the big fragment, due to momentum conservation, is necessarily directed in the forward direction. It is however important to show that a sequential statistical decay based on transition state formalism would predict at these energies emission of Intermediate Mass Fragment only if a large angular momentum is considered. The distribution simulated through SMM is more similar to the data, but still quite asymmetric, while the closer distribution to the experimental one is the one simulated by the dynamical code, CMD: this comparison gives in any case only a qualitative information, because CMD surely does not consider all structure information that could be still important at quite low energies. The only conclusion we can draw here is that more information is needed to understand what is really happening and whether also at low energy a real thermodynamical system has been formed or not. During the experiment also the measurement for the ^{32}S+^{64}Ni system was perfomed for a short time and the comparison between the two reactions shows some small but important differences. Are those structure effects still effective at relatively high excitation energy? Are they isospin effects which influence the phase diagram? In this case we also think that more data and investigations are needed.

6. Conclusions and outlooks

Different problematics have been addressed during studies using the GARFIELD facility: from measurements connected to applied physics, to those devoted to the study of a critical behaviour of nuclear matter, and to measurements connected to nuclear structure like the emission of GDR γ-rays at high excitation energy. The coupling between GARFIELD and the HECTOR detector have demonstrated to be a powerful tool to perform very clean measurements in which coincidences between charged products and γ-rays can be easily collected. This will help in better understanding the phenomena which occur in the relatively high excitation energy region, both from the side of reaction mechanisms and from the side of nuclear structure. Having in mind that there are still many interesting problems to face we are planning to perform new and different measurements around the $A = 100$–130 mass region aimed at studying all the possible systems which could be reached using the LINAC ALPI of LNL in the next future at relatively high excitation energy, in the main frame of a new experimental program called NUCL-EX.

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