LETTER OF INTENT

Nuclear Dynamics at LNL: emission of particles and fragments from excited systems

The NUCL-EX collaboration

Introduction

Since several years the NUCL-EX collaboration performs experiments with heavy-ions to explore both the nuclear equation of state (EOS) and non-equilibrium phenomena developing at the early phases of the collisions. These two general issues, concerning nuclear thermodynamics and dynamics, are being studied by NUCL-EX at the INFN italian laboratories, using the available detector arrays. The LNS at Catania is the reference laboratory as far as dynamics studies are concerned, mainly because the beam energies delivered there allow nuclear systems to enter the "Fermi" energy domain, where non-equilibrium effects are more evident. However, there are some aspects, briefly discussed hereafter, which can be studied at the lower energies of LNL, as soon the full mass/energy spectrum foreseen for the ALPI-PIAVE complex becomes available.
An important point we want to stress is that at LNL our collaboration (at variance with the LNS case where the CHIMERA detector [1] has been borrowed) has the responsibility of the GARFIELD apparatus. This detector system has been recently upgraded with both new telescopes and new digital electronics [2] to largely improve isotopic separation of the reaction products.

This letter of intent aims at evidencing our wish of continuing esperimental studies on nuclear dynamics at Legnaro, provided the full operation of the ALPI-PIAVE complex is reached next year. Therefore, we ask the PAC to strongly support a quick recovery of the XTU-ALPI-PIAVE accelerators so that Nickel and lighter beams at the maximum energies (15 AMeV for Ni) can be available. The proposal will be presented on the next PAC call in 2006.

Physics case

A large emission of neutrons, light charged particles (LCP) and intermediate mass fragments (A$\leq$20, IMF) characterizes heavy-ion collisions in the Fermi energy domain (20-100 AMeV) [3–7]. Different sources, characterized by different time scales, have been recognized as responsible for these emissions. One of the purposes in this field of nuclear physics is to describe the origin of these emissions, which often overlap in time and phase-space, thus making their identification rather challenging. A proper event selection, to distinguish peripheral, semiperipheral and central collisions, and a precise emission source identification are mandatory steps for the comprehension of the underlying phenomena. Modern and efficient detectors are needed for this purpose.
Among the many examples existing in the literature, our previous works have focused on the emissions of LCP and IMF occurring in semiperipheral reactions [4, 5]. These reactions are essentially binary with the production of and excited quasi-projectile (QP) and quasi-target (QT). Basing on a careful data analysis, we could disentangle the "normal" evaporative emission of the QP and QT from the mid-velocity (MV) component, i.e. a component coming from the phase-space region in between the QP and the QT. The role of these fast MV emissions in determining the fate of the collision, namely the size, the charge, the angular momentum and the excitation energy of the final QP and QT is extremely important; moreover, the features of MV ejectiles are connected with the properties of the EOS of excited nuclear systems and with the instabilities of the nuclear matter when it is strongly deformed and/or heated. Recent theoretical studies [8, 9], also in view of the present and future exotic beam facilities, have underlined the link between these fast emissions and the dynamics of the N/Z (isospin) degree of freedom, sensitive to the density gradient.
The properties of the MV emissions have been studied by our group by pursuing a quantitative estimate not only of the mass and charge of this source, as done by other authors (e.g. [6]), but also of the

total energy removed from the system. This mass and energy balance is quite important to describe the production of hot systems which can then enter the coexistence liquid-gas region and possibly produce multifragmentation. We stress here the strong overlap between this kind of "dynamical" study and the thermodynamical approach: thermodynamical concepts can be applied to finite nuclear systems [7, 11] once their identity and global parameters have been established and this needs a full and precise characterization of the dynamics at work [12].

The above mentioned subjects have been investigated with the FIASCO apparatus at the LNS, studying semiperipheral collisions for the systems $^{93}Nb +^{93} Nb,^{116} Sn$@23, 30, 38 AMeV. To better address the origin of the MV emissions, putting in evidence the role of nucleon-nucleon interactions versus collective processes in the overlapping hot region, in 2004 the NUCL-EX collaboration extended the studies at the LNS with the CHIMERA detector [1], by moving along the mass-asymmetry coordinate and the bombarding energy: the systems $^{58}Ni +^{58} Ni,^{112} Sn$ have been measured at 35 and 45 AMeV. The analysis is in progress and will also benefit from the theoretical hints recently proposed on the neck-isospin dynamics [9, 10].
We are now planning a series of measurements at LNL to answer the following questions: how fast do LCP and IMF emissions scale down with relative velocity? How do entrance channel effects enter in the production of MV fragments at lower energies? These subjects connected to non-equilibrium processes have been studied in the past at energies below 20 AMeV [13–15] but information is rather scattered and incomplete, while a simultaneous and comprehensive investigation on the emitting sources (QP,QT,MV, very forward emitted preequilibrium particles) has not been performed, because of the lack of $4p$ arrays in previous measurements. We therefore plan to investigate symmetric and asymmetric[16] systems at energies at which dynamical effects are probably at the thershold, with an efficient detector like GARFIELD and with modern analysis techniques like those developed by our group.

Proposed experiments with Nickel beams

It would be interesting to perform an experiment at LNL on $^{58}Ni +^{58} Ni$ about 15AMeV, whose results can constitute in some sense a "reference point". In fact such systems, and more generally the emissions from Nickel-like excited nuclei, have been previously studied by our collaboration and by other authors at various energies [7, 17–20] and a rich quantity of data and indications is available. Different aspects have been evidenced, going from the statistical rare IMF emission of the compound nucleus [19], at low energies, to the contemporary MV emission and multifragmentation of QP [7] or to the dynamical rupture of deformed QP at Fermi energies [18]. Most of the low-energy data [19, 20], however, refer to the decay of the compound nucleus (A≈116) which is formed in central collisions and which represents just one (though possibly the most abundant) source of complex fragments; also recent proposals with exotic beams from the SPIRAL facility concentrate on CN events [21].
In other words, information on dynamical effects in less central events at these energies is missing. At the Legnaro beam energies, expecially for symmetric systems [22], non-equilibrium emissions should be rather weak and one should describe the decay of the QP and QT mainly by means of statistical concepts [23]. On the other hand there exist experiments which focussed on non-equilibrium at these energies but they are rather scarce and conceptually "old" in the sense that they were not based on large acceptance array, such as GARFIELD, which allow a (almost) full event reconstruction. Therefore, the nature and the relevance of these emissions have not been clarified yet and systematic studies are lacking. For example, signals for non-equilibrium emissions have been proposed but the question whether direct processes (knock-out or break-up) or more collective phenomena (neck emission) come into the game is not answered. Evidences for the first type of processes have been found in reactions with asymmetric systems and are possibly enhanced by the internal cluster-structure of light ions̃citegadio. More collective non-equilibrium phenomena probably show up in heavier and symmetric systems: pre-scission LCP and neutron emissions or fast-oriented fission are probably the low-energy precursors of MV emissions as seen in the Fermi domain.

In this respect it will also be interesting to study the LCP and IMF non-equilibrium emissions as a function of the neutron vs. proton content. Recent theoretical papers [8–10], though referring to higher

energy collisions, suggest that strongly deformed transient structures, potential sources of MV LCP and IMF, are quite affected by the isospin variable; moreover, isospin dynamics controls the partition of neck-like systems in gas-like particles (free neutrons and protons) and liquid drops (clusters). Thus it will also be interesting to measure the n-rich system $^{64}Ni +^{64} Ni$, looking for differences in the yields and chemical compositions of LCP and IMF with respect to the n-poor system. With the cross systems $^{64}Ni+^{58}Ni$ and $^{58}Ni+^{64}Ni$, one should check the N/Z relaxation times by measuring isospin distributions for QP and its associated particles: an equilibrium state in this variable should be signed by the lack of any difference in the two cases. This signal could be also investigated as a function of the impact parameter.
Finally, the measurement of the two n-poor and n-rich systems will allow to better study odd-even effects observed for the distributions of the final fragments. Previous works, some of them just on Ni decay, have shown an enhanced production of even-Z fragments in binary collisions, persisting at relatively high bombarding energies (25 to 75 AMeV) [17, 24]. Indications of odd-even structures have been recently found by our group in a recent thermodynamical study [25]. In Ref [17, 24] these effects were explained in the framework of statistical model where the details of the fragment isospin distribution play a significant role. Thus it could be interesting to investigate this subjet at lower energies. In particular, new results at the low LNL energies on the n-poor Nickel system could be directly compared with those of Ref. [17] obtained between 45 and 105 AMeV.

[1] S. Aiello *et al.* Nucl. Phys. A583 (1995) 461,
[2] L. Bardelli *et al.* Nuclear Phyis A, 746 (2004) 272c,
[3] M. Metivier *et al.* Nucl. Phys. A672 (2000) 357,
[4] S. Piantelli *et al.*, Phys. Rev. Lett., 88, (2002) 052701,
[5] A. Mangiarotti *et al.*, Phys. Rev. Lett., 93, (2004) 232701,
[6] J. Łukasik *et al.*, Phys. Lett. B 566 (2003) 76,
[7] P.M. Milazzo *et al.* Phys. Lett. B509 (2001) 204,
[8] M. DiToro *et al.*, Prog. Part. Nucl. Phys. 53, (2004) 81,
[9] R. Lionti *et al.*, nucl-th/0501012, 2005,
[10] V. Baran *et al.*, Nucl. Phys. A730 (2004) 329,
[11] M. D'Agostino *et al.* Nucl. Phys. A749 (2005) 55,
[12] E. Gadioli *et al.* Eur. Phys. J A17 (2003) 195,
[13] D. Pelte *et al.*, Phys.Rec. C36 (1987) 1397,
[14] U. Winkler *et al.*, Zeit Phys. A 425 (1984) 573,
[15] M. Korolija *et al.*, Zeit Phys. A327 (1987) 237,
[16] V. Kravchuk *et al.*, see Proposal for the present PAC Session,
[17] L.B. Yang *et al.* Phys. Rev. C60 (1999) 041602,
[18] R. Moustabchir *et al.* Nucl. Phys. A734 (2004) 15,
[19] M. Balasubramaniam *et al.*, Journ. Phys. G 29, (2003) 2703,
[20] J. Gomez del Campo *et al.*, Phys.Rec. C43 (1991) 2689,
[21] J. Gomez del Campo *et al.*, SPIRAL proposal, 2005,
[22] O. Wieland *et al.*, submitted to Journ. of Phys. G,
[23] J. Boger *et al.*, Phys. Rev. C49 (1994) 1576,
[24] E.M. Winchester *et al.*, Phys. Rev. C63 (2000) 014601,
[25] Gramegna *et al.* Fizika B12 (2003) 39