Title: Dynamics & Thermodynamics of exotic nuclear systems

Spokesperson(s) *(max. 3 names, laboratory, e-mail - please underline among them one corresponding spokesperson):*

F. Gulminelli (LPC-ENSICaen, Caen, France, e-mail: gulminelli@lpccaen.in2p3.fr)
G. Poggi (INFN & University, Florence, Italy, e-mail: giacomo.poggi@fi.infn.it)
G. Verde (INFN, Catania, Italy, e-mail: giuseppe.verde@ct.infn.it)

GANIL contact person

J. Frankland (GANIL, Caen, France)

Collaboration *(names and laboratories):*

FRANCE:

IPNO (Orsay): E. Bonnet, B. Borderie, E. Galichet, N. LeNeindre, M.F. Rivet
GANIL (Caen): A. Chbihi, J. Frankland, J. Moisan, J.P. Wieleczko
LPC-ENSICaen (Caen): S. Barlini, R. Bougault, C. Ducoin, F. Gulminelli, G. Lehaut, O. Lopez, B. Tamain, E. Vient
IPNL (Lyon): D. Mercier, D. Guinet, P. Lautesse

INDIA:

VECC (Calcutta): S. Bhattacharya, C. Bhattacharya, S. Kundu, G. Mukherjee, K. Banerjee, T. K. Rana, T. K. Ghosh

ITALY:

Bologna (INFN & University): M. Bruno, J. De Sanctis, M. D'Agostino, E. Geraci, P. Marini, G. Vannini
Catania (INFN): M. Baldo, G. Verde
Catania (LNS): A. Bonasera, M. Colonna, M. DiToro
Firenze (INFN & University): L. Bardelli, M. Bini, G. Casini, M. Chiari, A. Nannini, A. Olmi, G. Pasquali, G. Poggi, S. Piantelli, A. Stefanini
LNL (INFN): M. Cinausero, M. Degerlier, F. Gramegna, V. Kravchuk
Napoli (INFN & University): M. La Commara, A. Ordine, E. Rosato, G.Spadaccini, M. Vigilante

POLAND:

Krakow (Jagiellonian University): A. Becla, T. Kozik, Z. Sosin, A. Wieloch
Katowice (Silesian University): A. Grzeszczuk, S. Kowalski, W. Zipper
Warsaw (Warsaw University): A. Kordyasz, E. Piasecki

ROMANIA:

Bucarest (NIPNE): R. Borcea, A. Buta, F. Negoita, M. Parlog, H. Petrascu, M. Preda, A. Raduta
Bucarest (NIPNE-HH and University): V. Baran

SPAIN:

Huelva (Universidade): I. Martel Bravo, D. Rodriguez, J.L. Flores Garrido, P. Salmeron Revuelta, J.M. Andujar

UNITED KINGDOM:

CCLRC Daresbury Laboratory: R. C. Lemmon

USA:

Kalamazoo, MI (Western Michigan University): Michael A. Famiano

Abstract:

The future availability of Spiral2 beams will allow us to study the properties of nuclear systems far from the valley of stability. These studies will provide unique information about the spectroscopic properties of nuclei close to the limits of their existence. Spiral2 beams will also provide tools to explore heavy-ion collisions at different impact parameters leading to the production of hot nuclear systems under exotic conditions of shape, excitation energy, spin and N/Z asymmetries (isospin). Moreover, these conditions can be experimentally controlled by choosing appropriate entrance and exit channels. This allows one to probe the mechanisms of nuclear excitation, how intrinsic degrees of freedom are converted into collective modes, how these modes decay and how relaxation processes occur within a small-many body quantum system that is initially far from equilibrium. The velocity and the angular distribution of the reaction products furnish natural clocks from which it is possible to determine the equilibration times of the various degrees of freedom (e.g. N/Z ratio, mass, excitation energy) and discuss whether non-equilibrium features in light particle and complex fragment emissions are present.

In this letter, we propose to study the dynamics and thermodynamics of excited exotic nuclear systems produced in reactions induced by Spiral2 beams. In the following sections we discuss topics that can be addressed with fusion reactions and deep inelastic collisions. Accessing the thermal and dynamical properties of exotic nuclei with high-resolution detectors will provide important constraints on the isovector part of the nuclear effective interaction, exploring also relevant features of the equation of state of asymmetric nuclear matter.

Scientific case (references in annexe-1)

Limiting temperatures in hot N/Z asymmetric nuclear systems

Experiments performed with stable beams have produced hot nuclear systems and their decay modes have been extensively investigated. From the properties of the emitted particles (energy spectra, isotopic yields, population of internal unbound states), information about the excitation energy and the temperature of these hot systems has been extracted [Sur89]. Theoretical calculations have predicted the existence of a *limiting temperature*, T_{lim} [Bon84, Bes89, Son93, Son91, Son94, Zha96, Bal99, De97, Wan05]. At low temperatures, $T \leq T_{lim}$, the nuclear system can be described as a nuclear drop evaporating light particles. Above limiting temperatures, $T > T_{lim}$, the thermodynamically equilibrated nuclear drop cannot survive anymore and breaks up. This limiting temperature regime has been theoretically predicted and experimentally observed.

From a theoretical standpoint, calculations based on Skyrme-type nucleon-nucleon interactions and other parameterizations have predicted mass-dependent limiting temperatures [Son91, Zha96, Bal99], with heavier nuclear systems being characterized by a lower T_{lim} value. Such A-dependence of T_{lim} is predicted to provide important information about the critical temperature, T_C, of infinite nuclear matter and about the isoscalar part of the nucleon-nucleon effective interaction [Son91, Zha96, Bal99]. Experimentally, a systematic study of limiting temperatures has been performed by J. Natowitz et al. [Nat02]. By collecting all the available data on nuclear caloric curves (i.e. the correlation between measurements of excitation energy and temperature), a decreasing limiting temperature with increasing mass of the hot nuclear system has been experimentally observed [Nat02]. Based on comparisons with theoretical calculations, the observed mass-scaling of T_{lim} has been associated to an effect of Coulomb instabilities becoming more and more important as the amount of protons in heavier systems is increased [Nat02]. These studies were performed with stable beams leading to the production of hot nuclear systems with small N/Z asymmetries. Systems close to the stability line are characterized by high limiting temperatures (T_{lim}~6-9 MeV) [Nat02, Zhu04]. However, theoretical calculations predict that T_{lim} decreases significantly as one moves away from stability. The authors of Refs. [Bes89, Zhu04] have mapped T_{lim} as a function of N and Z, predicting that very N-Z asymmetric nuclear systems are expected to be characterized by a significantly lower limiting temperature. The attenuation of T_{lim} away from stability is predicted to be induced by a combined effect of Coulomb instabilities and the symmetry energy [Bes89, Zhu04]. These predictions suggest that it will be possible to achieve and explore the limiting temperature regime of exotic nuclei with large N/Z asymmetries even at the low incident energies available at Spiral2. By producing compound nuclei with the same mass number, A, and different N/Z asymmetries, one can explore the N/Z-dependence of T_{lim}. This will allow one to enhance the effects of the symmetry energy as one moves towards more neutron rich species and the effects of the Coulomb instabilities as one approaches the proton-rich side of the nuclear chart. These studies will provide relevant information about the nuclear symmetry energy and on the isovector part of the nucleon-nucleon interaction. The research program can be further extended in a second phase involving the use of higher energy beams delivered by the Eurisol facility. However, the energy range of the Spiral2 facility will already provide enough tools to significantly extend the present reach in understanding the properties of exotic and hot nuclear systems.

N/Z dependence of nuclear level densities.

The density of nuclear levels is a fundamental quantity in nuclear physics which plays an essential role in understanding compound nuclear reactions. It is also a basic ingredient for the determination of thermonuclear rates for astrophysics, with applications both in nucleosynthesis and supernovae dynamics [Don94,Rau97]. While the level density around the Fermi surface depends critically on nuclear structure details [Orm97], at higher energy it can be effectively parameterized via a mass, isospin and temperature dependent level density parameter a(A,Y,T) and possibly a backshift Δ accounting for pairing effects [Orm89,Buc05]. In the high temperature regime (above 2 MeV) level densities can not be realistically predicted by microscopic theories due to the finite model space of any shell model calculation, and have to be experimentally measured. Although experimental evidences already exist on the initial increase [Orm89] and successive decrease [Lun02] of the level density parameter with increasing temperature, no complete realistic parameterization is available yet. In particular the N/Z dependence of the level density parameter “a” will give unique information on the largely unknown temperature dependence of the symmetry energy. This program can be accomplished by coincidence measurements of isotopically resolved residues with the emitted light particles over the whole solid angle. Such a measurement will provide unique constraints on the level density used in Hauser-Feshbach or Weisskopf calculations.

This program is the natural extension to higher excitation energies and angular momentum of level density measurements with gamma detectors [Aga04].

Two- and multi-particle correlation studies and validity of statistical theories

Spiral2 beams will allow to produce a large variety of moderately excited nuclear systems. The decay of such systems has extensively been described by means of statistical models [Wei37, Eri60]. These models are commonly based on a fundamental assumption of Statistical Thermodynamics: in a microcanonical ensemble (well suited to describe isolated systems such as hot nuclei) all the available final states have the same probability to be populated. This probability is calculated by means of the Fermi Golden Rule where the level density is the main ingredient depending on available excitation energy and angular momentum. Kinetic energy spectra of evaporated particles have been observed to be characterized by Maxwellian shapes whose slope has been used to determine temperatures. The observation of similar slopes for different particle species corroborates the validity of the basic assumptions of the statistical theory. However, experiments have demonstrated the validity of the statistical theory only by studying the decay of several identical nuclei produced in fusion events or in deep inelastic collisions for which the kinetic energy spectra represent inclusive observables constructed by collecting in the same spectrum particles emitted in different events. These single-particle analyses provide limited information since the correlations between successive particles emitted in the same event are lost. Especially in the study of exotic excited nuclei, these correlations can be particularly important. For example, N/Z asymmetric nuclei at moderate excitation energies are expected to display exotic spectroscopic features such as quasi-molecular states [Fre01, Orr99] and decay modes that cannot be predicted by the Weisskopf theory. Only two- and multi-correlation studies can be used to study exotic phenomena such as clustering and quasi-molecular features [Fre01, Orr99, Gue73]. A detailed study of the de-excitation of compound nuclei by means of correlation techniques and the use of Spiral2 beams will offer the opportunity of exploring the N-Z-dependence of de-excitation processes and perform stringent tests of the theories of statistical decay.

Accessing the nuclear symmetry energy from fragment isotopic distributions.

In reactions at intermediate energies, the isotopic distributions of complex fragments can be used to extract information about the density dependence of the symmetry energy [Tan03, Liu04, Ono04]. Such information plays a key role in determining properties of neutron rich nuclear matter in neutron star crusts [Pet95, Lat01], as well as cooling properties of proto-neutron stars [Pag04,Yak04]. In particular, it is possible to show that the width of the isotopic distributions of the primary fragments produced at freeze-out is directly related to C_{sym}/T where C_{sym} and T are, respectively, the nuclear symmetry energy coefficient and the temperature of the of decaying system.

However, quantitative information about the symmetry energy is difficult to extract: “secondary decays” of excited primary fragments can distort signatures of the symmetry energy contained in primary fragment isotopic distributions. Previous studies have shown that these primary unstable fragments are characterized by excitation energies of the order of 3 MeV/nucleon before they undergo secondary decays [Mar98]. By means of Spiral2 beams we may be able to produce selected compound nuclei at excitation energies of 3 MeV/nucleon, analogous to the primary fragments in fragmentation phenomena. The detailed decay paths for these primary fragments can be studied by means of two- and multi-particle correlations, as it was already mentioned in the previous section. Understanding the competition between different open channels and how the fragment N/Z composition evolves with time during secondary decays can significantly improve our search for signatures of the symmetry energy in nuclear reactions.

The symmetry energy of an excited nucleus can also be directly probed in the evaporative regime from the so called isoscaling parameter, measuring the relative production yield of a given isotope in two reactions involving nuclei of similar masses and different isospin ratios [Tsa01]. While the fragmentation regime, inaccessible to SPIRAL2 beams, is needed to probe the symmetry energy at low sub-saturation energies, the temperature dependence of C_{sym} around saturation, at moderate to high temperatures is presently a subject of debate [Lef05,Xu06]. An iso-scaling analysis of fusion events with SPIRAL2 beams will give a definitive answer to this open question.

Studies with dissipative peripheral collisions and probes of the symmetry energy.

Dissipative mid-peripheral collisions, including binary and three-body breakings, offer a unique opportunity to study a wide range of phenomena occurring in excited and N/Z-asymmetric nuclear matter. The study of dissipative reactions is also a necessary effort in research with unstable beams. Indeed, the impact parameter boundaries delimiting different reaction mechanisms (direct reactions, multi-nucleon transfers, deep inelastic collisions, fusion) are also expected to change drastically when beams of nuclei with extreme neutron/proton contents are used.

Beams with exotic isospin contents can induce changes in classical two-body dissipation mechanisms of typical deep inelastic collisions at low energies with stable beams. Deformations and emissions from the neck low density region between projectile and target can provide important probes of the symmetry energy. At low energies, interaction times are quite long and therefore a large coupling among various mean-field modes is expected. In some cases, due to a combined Coulomb and angular momentum (deformation) effect, some instabilities can show up, like in fission decays [Col95]. This can lead to three-body breakings, where a light cluster is emitted from the neck region [Dav79, Def05].

The development of surface (neck-like) instabilities, contributing to ternary breakings can certainly provide access to the isovector part of the nuclear interaction through a detailed comparison with transport models predictions. Stochastic mean-field (SMF) model simulations [Bar05] of ^{132}Sn+^{64}Ni collisions at E/A=10 MeV and impact parameters b=6, 7, 8 fm have shown a sensitivity of the neck dynamics to the detailed density dependence of the symmetry energy [Dit06]. Two different density dependence parameterizations are commonly explored, referred to as “asy-soft” and “asy-stiff”. Larger deformations of the di-nuclear system, possibly inducing a final three-body break-up, are more easily observed in the asy-stiff case. Such deformations are due to a long-lived neutron-rich neck connecting the two reaction partners and eventually dynamically emitting small clusters. In this respect, an asy-stiff symmetry term seems to lead to more dissipative events.

Dissipative reactions induced by ^{132}Sn beams at Spiral2 can therefore be used to experimentally probe the symmetry energy. Fragment-fragment velocity correlations and deviations from Viola systematics, fast fission of primary residues and alignment phenomena represent observables useful to isolate three-body events and study their features.

Isospin diffusion and equilibration between the reaction partners plays a key role in the dynamics of dissipative collisions at non-zero impact parameters [Tsa04]. The amount of neutrons and protons exchanged depends on the N/Z asymmetry of the colliding nuclei and on the density dependence of the symmetry energy [Tsa04]. Peripheral collisions between differently isospin asymmetric beam/target combinations can indeed provide quantitative information about the symmetry energy, once confronted with transport models simulations. At intermediate energies, the interaction time is short enough to stop the diffusion process before reaching the complete isospin equilibration [Tsa04]. As the beam energy is lowered below 20 MeV/nucleon interaction times are longer and one can expect to achieve more easily isospin equilibration between projectile and target. However, these considerations may change as one uses very N/Z asymmetric beams. Furthermore, the interaction time available for neutron/proton transfer depends on impact parameter. Deep inelastic collisions with both neutron and proton rich projectiles can therefore be investigated to study the achievement of isospin equilibration. The isotopic composition of quasi-protjectiles and quasi-targets and their velocity and angular correlations are expected to provide tools to explore the role of the symmetry energy in the process of dissipation and proton/neutron exchange.

Dissipative binary collisions of heavy ions give access to isotopic cross sections and their angular and energy distributions. Roughly driven by the ground state Q value - the Q_{gg} systematics - these values are sensitive to the proton P(Z) and neutron P(N) pairing corrections, even though the way to evaluate the latter ones is not unique [Boh98, Gil65].

For example, in very asymmetric systems studied in direct kinematics, many nucleons are transferred from the light projectile (from C to Ar) to the heavy target (from Zr to Th) and the logarithm of the isotopic cross section of the detected projectile-like fragment (the donor) is reported to depend almost linearly on the Q_{gg} value corrected for the pairing effect in the complementary target-like fragment (the accepter): $Q_{gg} - P(N)_{accepter}$ (for a given Z_{donor}) as long as $Z_{donor}<10$ [Vol78]. In fact, one may find that even more important is the pairing correction in the donor: $P(N)_{donor}$ because it is lighter; by taking both of them into account: $Q_{gg} - P(N)_{donor} - P(N)_{accepter}$ (P(N) from [Gil65]) the cross section pattern is much enlightened over the whole range of ejectiles.

Extending to neutron/proton rich beam-target combinations and eliminating the experimental ambiguities by complete measurements possible with the present instrumentation (in reverse kinematics too), these studies will allow to learn about neutron-neutron, proton-proton and eventually neutron-proton pair correlation in case of extremely exotic nuclei and to bring usefull pieces of information for the nuclear symmetry energy too.

For more central collisions, the equilibration mechanism can be studied via the direct measurement of prompt dynamical dipole emission, nucleus-nucleus collective bremsstrahlung radiation during the charge equilibration path [Sim00, Bar05, Pap05a, Pap06]. Experimental features of such dipole radiation are the angular anisotropy and the gamma spectrum, with centroid at energies well below the expected GDR emission from the residues. The energy range around 10 A.MeV seems to optimize the effect [Pie05].

Methodology (Typically 2-3 pages)

Beam properties *(primary beam, RIB: nature, intensity, time resolution, purity, use of beam tracking detectors etc. - to be specified if possible):*

A somewhat large “panoplie” of n-rich and p-rich beams is necessary with bombarding energies above the Coulomb barrier and up to the maximum SPIRAL2 possibilities. Needed properties for the beam are:

- Good timing (better than 1ns) is necessary (bunchers). Technical solutions meant to guarantee Time of Flight measurements even in presence of a relatively poor time quality of the beam are under preliminary study.
- Intensities greater than or equal to 10^6 pps are needed.
- Purity of the beam is required. In case of impurity, technical solutions is order to tag the beam are necessary.
- Small beam spot is necessary (less than about 3mm).

We list some key N/Z asymmetric projectile/target combinations that could be used to carry on the proposed research program:

– Medium mass systems

^{78}Zn+^{64}Ni, ^{94}Kr +^{50}Ti, ^{96}Sr + ^{48}Ca, ^{72}Kr + ^{50}Ti

– Heavier mass systems

$^{114\text{-}145}$Xe +^{40,48}Ca, ^{122}Cd + ^{58}Ni, ^{90}Kr + ^{90}Zr

The incident energies required by the proposed research program range between E/A=5 MeV and the maximum energy that can be achieved with the Spiral2 facility. With these reactions one can produce chains of isotopes as compound nuclei all with the same Z and different mass number A. These compound nuclei can be used to investigate on isospin effects on limiting temperatures and on level densities. Furthermore, reactions such as ^{72}Kr,^{78}Kr + ^{28}Si and ^{74}Zn, ^{80}Zn + ^{26}Mg allow to produce other compound nuclei with the same mass but with different Z-values. This is particularly useful to isolate mass and isospin effects in limiting temperature measurements [Nat02]. The same reaction systems listed above can also be used to study dissipative collisions in order to search for effects induced by the symmetry energy even in peripheral reactions.

Stimulated by stochastic mean-field (SMF) simulations, we also propose to study the reactions

^{112,132}Sn+^{58,64}Ni at E/A=10 MeV

in order to explore three-body break-up events and neck fragmentation phenomena.

Two- and multi-particle correlation studies to explore the detailed de-excitation process of primary fragments produced in multifragmentation phenomena will require the production of light excited compound nuclei in the low mass region (A=20-30) and with different N/Z compositions. For this purpose, medium-light exotic (n-rich and p-rich) projectiles at CIME incident energies could be used.

Target(s) *(RIB production target, secondary targets: nature, thickness - to be specified if possible):*

Instrumentation and detectors *(equipment to be constructed or modified):*
We propose to accomplish our physics goals by studying fusion and deep inelastic reactions induced by beams with various N/Z asymmetries. Such studies and the possibility of exploring the isospin degree of freedom require specific detection capabilities. The FAZIA working groups have already started studying the possible technical choices and designs required to accomplish these detection capabilities [Faz06]. In this respect, the proposed scientific program can be explored even in the framework of the first phase of the 4π−FAZIA project, covering a reduced solid angle with an angular resolution high enough to study correlation observables, and coupled to other detector setups.

From an experimental point of view, to fully exploit the SPIRAL2-Radioactive Nuclear Beams (RNB) facility and study the effects of large isospin variation, the accomplishment of both Z and A identification of particles and fragments over the largest possible ranges is necessary. The present identification techniques (Time of Flight, Telescope DE-E) do not allow fulfilling the identification requirement on a large dynamical range. Several multi-detector systems are currently being intensively exploited at European nuclear physics facilities and are generating major advances in the scientific fields described above. For the study of nuclear dynamics and thermodynamics, current state of the art arrays include INDRA (1993, France) and CHIMERA (1999, Italy) and GARFIELD (2000, Italy). At present, experimental results from INDRA and CHIMERA collaborations are considered as the reference in the worldwide competition for heavy-ion studies in the Fermi energy regime and partly above. However the mass and charge identification of these apparatuses are not as such as to fully benefit from radioactive beams, in particular at the SPIRAL2 energies. For those beams, very low A and Z identification threshold has to be obtained. This will only be achievable through the development of Pulse Shape Discrimination (PSD) techniques and the corresponding electronics. On the basis of the results already reached in the framework of the FAZIA collaboration, one may realistically aim at full Z and A identification up to Z~20, with energy thresholds a factor of at least three smaller than the preceding apparatuses. Moreover the granularity must also be improved and a device design aimed at complementing the apparatus with other facilities (in particular spectrometers) is necessary. Details of the current progress in the frameworks of FAZIA can be found in [Pog06, Faz06] and a brief description of the R&D under way is reported in the Annex 2.

To summarize, for SPIRAL-2 studies a new apparatus is needed with the following main characteristics (see annexe-2 for details):

- Large fraction of the forward solid angle coverage
- High granularity for reverse kinematics experiments and nuclear interferometry measurements
- Extension, with respect to existing apparatuses, of the Z and A identification performances
- Low energy detection-identification thresholds
- Possibility to couple the array with existing present generation arrays to cover the full solid angle or to improve a particular detection capability over small solid angle

- Quasi-Projectile and Quasi-Target detection capability (coupling with a spectrometer is the adequate tool)
- Good timing (Time of Flight needed)
- Compactness of the device, to allow for addition of outer shells for neutral detection which would constitute an extremely important improvement of the setup
- Ease of calibration: (i) cocktail beam + properly designed mechanics to allows all-detector-illumination, (ii) Possible implementation of “automatic” calibration procedures to improve analysis efficiency (possibly “on-line”)
- Transportability: for measurements campaigns with exotic and stable beams delivered by different facilities (SPIRAL/SPIRAL2, LNL/ALPI/SPES, GANIL, LNS, GSI/FAIR/NUSTAR, EURISOL).
- Fully Digital Electronics is presently envisaged because of (i) compactness, (ii) flexibility in terms of signal treatment, (iii) feasibility of digital energy, digital pulse shape and digital timing [Bar06, Bar04, Bar04bis], with at most two digital channel per sensitive element (current and charge), (iv) high dynamic ranges, (v) improved transportability and (vi) possible implementation of on-line DSP-based calibration procedures.
- Fast large data flow acquisition system

Theoretical support *(short description of the necessary calculations and developments):*
All analyses on limiting temperatures and level densities will be systematically confronted to statistical calculations. Different statistical theories (Hauser-Feshbach, Weisskopf, transition state) and dedicated simulations (GEMINI, SIMON, ABLA, SMM, MMM…) will be needed. The analyses constraining the symmetry energy deeply rely on the comparison to transport codes (AMD, BNV, BUU, SMF, TDHF,…), and extensive numerical simulations will be performed. Theoretical improvements will also be necessary. The interplay in the reaction dynamics between the density functional and transport properties presently leads to huge error bars in the quantitative estimation of fundamental quantities, even if these uncertainties will be strongly reduced by the use of differential observables. Moreover the different approximation schemes developed in the different codes do not produce entirely compatible results. To improve their predictive power, the already started [WCI06] detailed comparison between different codes needs to be continued. On a deeper theoretical level, the continuation of this scientific program at higher energies will need improvements of the existing transport theories towards the inclusion of off-shell effects and correlations beyond the mean field which are presently treated at the classical level only.

Preliminary schedule of the process leading to the signature of the Memorandum of Understanding and of the construction of new equipment:

Studies for improving detector arrays for reaction dynamics are under way since many years and involve physicists which already gained experience by building existing devices, mainly INDRA, CHIMERA, FIASCO and GARFIELD; the co-operation was done in a French Italian initiative which now turns out to be a collaboration named FAZIA involving also Canada, India, Poland, Romania, Spain and the United States of

America. Recently, part of this collaboration defined a strategy for the next couple of years, mainly consisting in the development of a few detector prototypes with innovative solutions (financial support from IN2P3/CNRS and Agence Nationale de la Recherche in France, from INFN and Italian Ministry of Research and Education in Italy).

On that basis it is clear that the chosen strategy on the detector prototyping does not start from scratch. Nevertheless it has to be mentioned that the SPIRAL-2 dynamics and thermodynamics scientific program relies on an R&D-program which is an open initiative since this *R&D project may serve a larger community and may benefit of “external” expertise*. EURISOL working groups, spectrometers (coupling), FAIR/NUSTAR-RIB, neutron detection, direct reactions and AGATA are the synergies presently coming out.

FAZIA (Four π A and Z Identification Array)

Prototype-array development Phase aiming for the construction of a FAZIA-array adapted for SPIRAL2-beams.

The strategy is organized in three steps:

- FAZIA-PC: deep study of the detection mechanisms in Silicon and scintillation detectors, definition of the basic detection modules and of the identification approach and algorithms, R&D of the prototype cell (actual work: Silicon-nTD, Direct or Reverse configuration, CsI(Tl), Single Chip Telescope, Strip Silicon, Front End Electronics, DAC) to define the basic telescope cell
- FAZIA-PA: on the basis of the conclusion drawn in the preceding phase, design and construction of a prototype array (it will consist of about 20-30 basic telescope cells arranged in an array geometry which fulfill technical needs in terms of granularity and angular resolution for test of mechanical problems, cross-talks, DAQ, etc…).
- FAZIA-S2: construction of a FAZIA-array.

Milestones and deliverables are organized as described below:

- Ordering of the detector material: July 2006 (i.e. done).
- Front End Electronics for the basic telescope cell (preamplifier + charge and current digitizers mounted on the Firenze mother board): September 2006 (i.e. done).
- Defining geometry for the basic telescope cell: October 2006 (i.e. done).
- Construction of the basic telescope cells and assembling mechanics: November 2006.
- Implementation of the simplified DAQ: November 2006.
- Various tests in various laboratories: 2007.
- Test runs under beam of basic telescope cells and construction of the Pulse Shape Data Base: 2007.
- Decision of the chosen basic telescope cell: first semester of 2008

Then the same procedure is followed for the Prototype Array with end of 2009 as ending date with an adapted DAQ.

A technical design report which contains detailed information about energy, identification thresholds, ranges, geometry is produced in 2010 and serves as “green light” for building the FAZIA-array adapted for SPIRAL2-beams.

Preliminary evaluation of the cost of the equipment to be constructed as well as necessary manpower:

The estimated cost for the final 4π-FAZIA is about 8 MEuros. For SPIRAL2, the full solid angle coverage does not seem necessary and therefore a significant reduction of that figure is foreseen. The first step “FAZIA-PC” is already funded. A complete evaluation of the costs as well as necessary manpower for the steps “FAZIA-PA” and “FAZIA-S2” is in progress.

ANNEX 1: bibliography

[Aga04] International Workshop on Physics with AGATA, Orsay, March 22-24, 2004, contributions by S.Siem and P.Pizzochero
[Aud93] G. Audi & A.H. Wapstra, NPA 565, (1993).
[Bal99] M.Baldo et al., Phys. Rev. C59, 682 (1999)
[Bar04] L.Bardelli et al., Nucl.Phys.A746 (2004), 272.
[Bar04bis] L.Bardelli et al, NIMA 521 (2004) 480
[Bar05] V.Baran et al., Phys.Rep. 410, 335 (2005) and references therein
[Bar06] L.Bardelli, G.Poggi NIMA 560 (2006) 517
[Bes89] J.Besprosvany et al., Phys. Lett. B217 (1989)
[Bin03] M.Bini et al, NIMA 515 (2003) 497
[Boh98] A. Bohr & B.R. Mottelson, Nuclear Stucture, p. 143, p.169, World Scientifc Publishing Co. Pte. Ltd (1998).
[Bon84] P.Bonche et al., Nucl. Phys. A427, 278 (1984)
[Buc05] D.Bucurescu et al 2005 J. Phys. G: Nucl. Part. Phys. 31 S1675-S1680
[Col95] M.Colonna et al., Nucl. Phys. A589, 160 (1995)
[Dav79] K.T.R.Davies et al., Phys. Rev. C20, 1372 (1979)
[De97] J.N.De et al., Phys. Rev. C55, R1641 (1997)
[Def05] E. De Filippo et al., Phys. Rev. C71, 044602 (2005)
[DeS05] http://cyclotron.tamu.edu/wci3/newer/chapVI_1.pdf
[Dit06] M.Di Toro et al., Proceedings of the IX Nucleus-Nucleus conference, Rio de Janeiro, Aug.2006, Nuclear Physics in press
[Don94] P.Donati et al., PRL 72 (1994) 2835
[Eri60] T.Ericson, Adv. Phys. 9, 425 (1960)
[Faz06] Web site Fazia collaboration (http://fazia.in2p3.fr)
[Fre01] M.Freer, Nucle. Phys. A685, 146c (2001)
[Gil65] A. Gilber & A.G.W. Cameron, Canadian J. of Phys. 43, 1446 (1965).
[Gue73] D.Guerreau, PhD Thesis, Orsay, 1973
[Ham04] H.Hamrita et al NIMA 531 (2004) 607 and PhD thesis,tel-00010145
[Lat01] J.M.Lattimer et al., Astrophys. J. 550, 426 (2001)
[Lef05] A.Lefevre et al, PRL 94, 162701 (2005)
[Lis05] M. Lisa et al., Annu. Rev. Nucl. Part. Sci. 55, 357 (2005)
[Liu04] Phys. Rev. C69, 014603 (2004)
[Lpc06] S.Barlini et al., FAZIA-WG1 meeting (2006)
[Lun02] M.Lunardon et al, Eur. Phys. J. A 13, 419-428 (2002)
[Mar98] N.Marie et al., Phys. Rev. C58, 256 (1998)
[Mut00] M.Mutterer et al, IEEE Trans.Nucl.Science 47 n.3 (2000), 756
[Nat02] J.Natowitz et al., Phys. Rev. C65, 034618 (2002)
[Ono04] A.Ono et al., Phys. Rev. C70, 041604 (2004)
[Orm89] W.E.Ormand et al, Phys. Rev. C 40, 1510–1512 (1989)
[Orm97] W.E.Ormand,Phys. Rev. C 56, R1678–R1682 (1997)
[Orr99] N.Orr et al. Nucl. Phys. A654, 710c (1999)
[Pag04] D.Page, arXiv:astro-ph/0405196
[Pap05] M. Papa et al., Phys. Rev. C72, 064608 (2005) and Refs. therein

[Pap06] M. Papa et al., Phys. Rev. C73, 031601 (2006)
[Pet95] J.Pethick et al., Ann. Rev. Nucl. Part. Sci. 45, 429 (1995)
[Pia02] S.Piantelli et al. Phys.Rev.Lett. 88 (2002) 052701
[Pog06] G.Poggi, RN7 Conference Cortina July 2006
[Pie05] D.Pierroutsakou et al., Phys. Rev. C 71, 054605 (2005)
[Rau97] T.Rauscher et al., Phys. Rev. C 56, 1613–1625 (1997)
[Sim00] C.Simenel et al., Phys. Rev. Lett. 86, 2971 (2000)
[Son91] H.Q.Song et al., Phys. Rev. C44, 2505 (1991)
[Son93] H.Q.Song et al., Phys. Rev. C47, 2001 (1993)
[Son94] H.Q.Song et al., Phys. Rev. C49, 2924 (1994)
[Sur89] E. Suraud et al., Progr. Part. Nucl. Phys. 23, 357 (1989) and Refs. therein
[Tan03] W. P. Tan et al., Phys. Rev. C68, 034609 (2003)
[Tsa01] M.B.Tsang et al., Phys.Rev. C64 (2001) 054615
[Tsa04] M.B.Tsang et al., Phys. Rev. Lett. 92, 062701 (2004)
[Vol78] V.V. Volkov, Phys. Rep. 44, 93 (1978).
[Wan05] P.Wang et al., Nucl. Phys. A748 (2005)
[WCI06] "Dynamics and thermodynamics with nucleonic degrees of freedom", W.Trautmann et al eds, Springer 2006.
[Wei37] W.Weisskopf, Phys. Rev. 52, 295 (1937)
[Xu06] J.Xu et al, arXiv:nucl-th/0609035
[Yak04] D.G.Yakovlev et al., arXiv:astro-ph/0409751
[Zha96] Y. Zhang et al., Phys. Rev. C54, 1137 (1996)
[Zhu04] Z.Li et al. Phys. Rev. C69, 034615 (2004)

ANNEX 2: detailed methodology (instrumentation and detector)

The proposed scientific goals require the following detection capabilities:

- *Large solid angle coverage and high granularity*. A correct determination of the excitation energy deposited into the studied systems requires the exclusive detection of all reaction products to perform calorimetric measurements. One can envision 2π solid angle coverage in the forward direction with detectors for charged particles and possibly neutrons. The determination of the temperature from the slope of kinetic energy spectra will certainly benefit from measurements over a large angular range and extended to several nuclear species.
- *High isotopic resolution with low identification thresholds*. The search for isotopic effects in the de-excitation of compound nuclei and in deep inelastic collisions requires very good mass and charge identification capabilities. In this context, low identification thresholds are a key issue in the physics of the future Spiral2 facility. Indeed, the particles typically produced in reactions induced by low energy Spiral2 beams will be slow enough to make their identification very difficult with traditional DE-E techniques. It will be important to use new detection techniques based from one side on an improved knowledge of the Physics of the detection mechanisms and from another on an as best as possible signal treatment. This practically means to perform a detailed digitization of the shape of the signals (current and charge) induced by the passage of particles through the detection materials [Bar04, Ham04]. These techniques are expected to allow the determination of the mass and charge with satisfactory isotopic resolution even for complex fragments. Such capability is also important in view of detecting new decay channels that will possibly be opened in the study of compound nuclei produced with exotic beams. The FAZIA detection solutions are presently directed toward matching similar requirements.
- *High flexibility*. The importance of performing exclusive measurements of all reaction products will require the coupling between different detector setups. For example, the use of a magnetic spectrometer, coupled to an array of charged particle telescopes seems to be well suited to study fusion reactions with high accuracy. The spectrometer can be used to detect the residue of the evaporation chain (with precise determination of its mass, charge and momentum) while all the evaporated particles can be detected by a large-area charged particle array such as FAZIA. The same configuration could be used to study deep-inelastic collisions where the PLF can be well identified with the spectrometer while the slower TLF and other possible neck fragments can be detected and identified with FAZIA telescopes characterized by very low identification thresholds.

  More precise and complete information about the fusion events will benefit from the coupling of charged particle detectors to neutron and gamma ray detectors. The emission of neutrons can especially play a key role in reactions induced by very neutron rich beams.
- *High angular resolution.* The angular resolution is a key parameter in order to perform correlation measurements between the reaction products. Two-particle correlation functions can be used to determine emission temperatures and to

explore the space-time properties and deformations of the decaying system [Lis05]. Two-particle correlations can also provide important tools to disentangle pre-equilibrium emission from emissions associated to evaporation phenomena. By studying velocity-gated correlations between unlike particles one can also extract information about the emission chronology of different particles. This technique, applied to neutron-proton, proton-deuteron, proton-triton, etc. correlations could provide important information about the dynamical aspects of excited nuclear systems approaching the limiting temperature break-up regime. A good angular resolution is also of paramount importance for an accurate characterization of peripheral and quasi-binary reactions. In fact an accurate kinematic reconstruction of the reaction requires a high angular resolution to estimate the excitation energy sharing among the open reaction channels [Pia02, Bin03]. Correlation studies can also be performed with a dedicated device with high angular resolution and properly coupled to a reduced FAZIA and a spectrometer to better characterize the events. In this respect, the GASPARD array, described in the LoI on direct reactions studies for Spiral2, can certainly be considered as a valuable and highly performing technical option.

Mass and charge identification is one of the major challenges of particle detection systems. At present, two techniques are generally employed, time of flight and energy loss measurements. The former requires long flight paths which translate into large, expensive and somewhat cumbersome arrays. The latter implies high thresholds which preclude the identification of important low energy particles. More recently, particle identification through pulse shape analysis has been proposed and promising preliminary studies have been performed. The combination of the three techniques should open a path towards more compact and efficient arrays. We intensively investigate the potential of mass and charge discrimination through pulse shape analysis in both Silicon and CsI detectors. Research in this area includes a better understanding of the underlying detector Physics and the development of electronics (signal digitization), algorithms and materials (e.g. neutron transmutation doped silicon).

Multi-channel arrays comprising several thousands of channels cannot be conveniently instrumented with present day electronics. ASICs (Application Specific Integrated Circuits) can offer a high performance, compact, and integrated solution. The main challenges in the case of nuclear physics stem from the large energy ranges of the particles detected. We therefore concentrate on the development of ASICs for a high-dynamic-range front-end, timing and shaping electronics. Efforts are also directed towards ASICS for Pulse Shape Digitization (PSD), in close relation with the research on pulse shape analysis.

The "state of the art" [DeS05] concerning the detection and identification in charge and mass of the reaction products of heavy ion collisions at intermediate energies (few MeV-100 AMeV) is the following: the best resolutions in charge and mass are obtained with Silicon-Silicon or Silicon-CsI(Tl) telescopes (with preferred position sensitivity in order to properly correct the thickness inhomogeneities of the Delta E detector). The main limitations of this approach are the existence of both a low-energy threshold for charge identification (the particles must have enough energy to reach the second detector, punching through the first one, which for this reason should be thin) and of a high-energy threshold (high energetic particles produce small signals in the first detector, which for this reason should be thick). The measurement of the time-of-flight allows to determine the mass (but not the charge) of the particles stopped in the first detector. When the second detector is a CsI(Tl) scintillator (read out with a phototube or a photodiode) it is possible to perform a shape analysis of its signal and obtain an identification in charge and mass of the very fast charged particles (even though only up to charge 3 or 4): in fact it is well known that the fluorescence of CsI(Tl) depends on the ionization density of the detected particle, with fluorescence times varying from a fraction of to several microseconds. The shape analysis of the signals can also be used for charge identification of particles stopped in the first Silicon detector: in fact the shape of the signal depends on the ionization density of the detected particle in this kind of detectors too. The difficulty in this case is that the changes of the signal shapes occur on time scales of the order of few (or few tens of) nanoseconds, thus requiring particularly fast electronics. A better sensitivity to the ionization density can be obtained by mounting the Silicon detector in a "reverse" configuration [Mut00] with respect to the usual one, that is with the particles entering the detector from the rear side (the one opposite to the p-n junction) where the electric field is weak; the disadvantage is a general slowing down of the signals, with a corresponding worsening of the timing performances of the detector. All these identification methods require sophisticated electronic designs because, in order to obtain all necessary information, signal amplitudes (energy measurements) and arrival times of the particles (time-of-flight measurements) are to be determined as well as the shape analysis of the signals. Therefore a next generation detection setup with all these capabilities (shape analysis of the signals of the CsI(Tl) and especially of the Silicon Delta E detector) would be very complicated and very expensive if it were manufactured with the conventional approach, namely with analog electronics.

In order to fulfil the mentioned requirements, the FAZIA prototype is a telescope consisting of 3 detection layers: Delta E1 – Delta E2 – E. The first two layers will be made of Silicon material (300 and 500 micrometers thick), the last one of 4 cm of CsI(Tl). Digital electronics will be used.

For shape analysis of the signals, the detector response has to be as much as possible independent of the particle impact location. Therefore nTD-Silicon material as Delta E detector has been chosen because of precision target doping and better axial and radial uniformity: the doping of Silicon to create n-type Silicon is realized by neutron transmutation of ^{30}Si isotopes to ^{31}P after neutron capture and beta decay. This technique leads to resistivity fluctuation below 2% RMS as compared to 30% with regular Silicon detectors. Tests have been done with 200 and 600 mm^2 nTD-Silicon and a clear identification between ^{12}C and ^{13}C is achieved by pulse shaping for isotopes accelerated and then stopped in the detector [Ham04]. Experiments using CIME-beams in GANIL are in progress (June and September 2006). First results are positive: the identification method seems very promising for elements heavier than Carbon [Lpc06].

A second novel idea is the following: the Delta E2 - E telescope consisting of a Silicon detector followed by a CsI(Tl) scintillator could be manufactured without photomultiplier or photodiode; the new idea is that the Silicon is used not only to measure the ionization produced by the particles passing through it, but also to read out the fluorescence produced in the CsI(Tl) by the particles. With this method the electronic chain can be greatly simplified and made much more compact. The junction side of the Si detector must be optically coupled to the CsI scintillator. Therefore the particles passing through the Si and the CsI detectors give a composite current (or charge) signal, having a fast component (developing over tens of ns) associated with the ionization produced in the Silicon material and a slower component (times of the order of microseconds) due to the fluorescence of the CsI(Tl). It is therefore possible, by properly filtering the output of the preamplifier connected to the Si detector, to separate the two aforementioned contributions. The digital electronics is particularly efficient for an accurate shape analysis of the signal [Bar04]. This will allow the design and implementation of a compact telescope, able to identify mass and charge of the particles in the desired large energy range. An additional advantage of the disappearance of the photomultipier or the photodiode is the possibility of adding any extra-detection system behind the telescope (neutron detection for example).

In order to compare the advantages and drawbacks of the different technical solutions several prototypes are under construction with ANR/IN2P3-CNRS and INFN funds. Tests of (i) reverse and direct mounted configurations (Time of Flight versus pulse shaping), (ii) telescope with photodiode and without, (iii) possibility of using a strip nTD-silicon detector for Delta E1, (iv) Csi with different Tl doping will be made in 2007. Those developments are done by the FAZIA collaboration born in 2006; the basic idea is to develop a detector array for isospin-oriented reaction dynamics studies to be performed in a somewhat large bombarding energy range. The final goal is the construction of a unique detector array able to fulfill the needs for low energy (SPIRAL/SPIRAL2, LNL/ALPI/SPES) and higher energy (GANIL, LNS, GSI/FAIR /NUSTAR, EURISOL) studies with exotic and stable beams.