The Letter of Intent should be prepared using the following template and sent in electronic form (preferably as a pdf file) to the Chairman of the SPIRAL2 Scientific Advisory Committee *Muhsin Harakeh* (harakeh@kvi.nl) with a copy to the Scientific Co-ordinator of SPIRAL2 *Marek Lewitowicz* (Lewitowicz@ganil.fr) before **October 2nd 2006.** Further information on the facility and envisaged physics programme can be found at: http://www.ganil.fr/research/developments/spiral2/

Title: High-energy γ-rays as a probe of hot nuclei and reaction mechanisms

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Abstract:

Fusion-evaporation reactions induced by high intensity neutron-rich beams from SPIRAL2 will allow us to populate exotic compound nuclei, transferring more initial angular momentum to them (up to 100 $\hbar$) than currently achievable with stable beams. This will be of great benefit for the study of vibrational and rotational collective phenomena at finite temperature, such as the Giant Dipole Resonance or exotic shape changes induced by fast rotation. Heavy-ion radiative capture and reaction dynamics studies will also benefit considerably from the availability of high intensity neutron-rich beams. Gamma ray detection constitutes an important experimental probe common to all these physics topics. The present letter presents a proposal to construct a dedicated gamma-calorimeter with dynamical range from 100 keV to 50 MeV. Such a device might partly consist of existing European detectors. To complement the exciting challenges and opportunities afforded by SPIRAL 2, it is also the intention to investigate designs for a novel gamma-calorimeter benefiting from recent advances in scintillator technology.

Scientific case (Typically 2-3 pages)

The present proposal is put forward by groups interested in performing gamma-ray measurements using stable and radioactive beams from the SPIRAL2 facility. It addresses several distinct physics cases which have in common the motivation to study the various properties of hot and rotating nuclei. For some of the topics, the methods presented here are highly complementary to those tackled in other Letters of Intent.

The existing GANIL and future SPIRAL2 beams will allow us to study the properties and dynamics of hot exotic nuclei by measuring the high-energy γ-rays associated with the Giant Dipole Resonance (GDR)[1]. In particular, intense neutron-rich beams enable fusion-evaporation reactions to be used to populate neutron-rich compound nuclei at very high angular momenta (counterbalanced by the decrease of the fissility). A number of effects may be found in this high angular momentum regime including the Jacobi a) or other b) shape transition. The c) evolution of the GDR strength towards n-rich systems as well as its temperature and spin-dependence will greatly benefit from the future radioactive beams. The extreme N/Z ratios available with SPIRAL2 will significantly deepen our understanding of d) isospin mixing in heavy N=Z systems. The GDR-decay is also a useful tool for investigating reaction mechanisms. In particular, we are interested in probing the e) onset of multifragmentation-like phenomena, f) nuclear viscosity and fusion-quasifission dynamics as well as g) heavy-ion radiative capture. In some cases, not only the GDR is important but also the multiplicity, sum energy and angular distribution of the emitted γ-rays.

a) <u>Jacobi shape transitions</u> (contact: A. Maj, J. Dudek)
The Jacobi shape transition corresponds to a nuclear shape change at high angular momenta from oblate to triaxial and very elongated prolate configurations (cf. upper row of Fig. 1). It has been predicted[2] to appear in many nuclei in the liquid drop regime and is considered as a

[1] P. Bortignon, A. Bracco, R.A. Broglia, Giant Resonances: Nuclear Structure at Finite Temperature, Gordon Breach, New York 1998.
[2] K. Pomorski, J. Dudek, *Phys. Rev.* **C67** (2003) 044316; J. Dudek, N. Schunck, N. Dubray, *Acta Phys. Pol.* **B36** (2005) 975

gateway to hyperdeformed shapes. There are two principal signatures of Jacobi transitions: the splitting of the GDR strength function, and the "giant back-bend" observed in the rotational frequency of the E2 bump as a function of angular momentum, at the highest spins. So far firm evidence of a Jacobi transition has been found only in light nuclei: in ^{45}Sc in an inclusive GDR experiment by the Seattle group[3], and in ^{46}Ti in highly-exclusive GDR measurements using HECTOR+EUROBALL by the Krakow group of Adam Maj[4]. Also it was indicated in medium-mass nuclei by studying the giant backbend in the A=100 mass region by the Berkeley group[5]. The experimental study of the GDR γ-decay in ^{46}Ti (cf. lower-left part of Fig. 1) revealed other interesting phenomena related to the Jacobi shape transition: the Coriolis splitting of the GDR components at high rotational frequencies has been shown to play an important role in lowering and better separating the frequency of the vibration along the long axis. In addition, a preferential feeding of highly deformed structures in the residual nucleus ^{42}Ca by the GDR low energy component has been observed. A similar effect was also found in the super-deformed ^{143}Eu nucleus by the Milano group of Angela Bracco[6], also in a HECTOR+EUROBALL experiment.

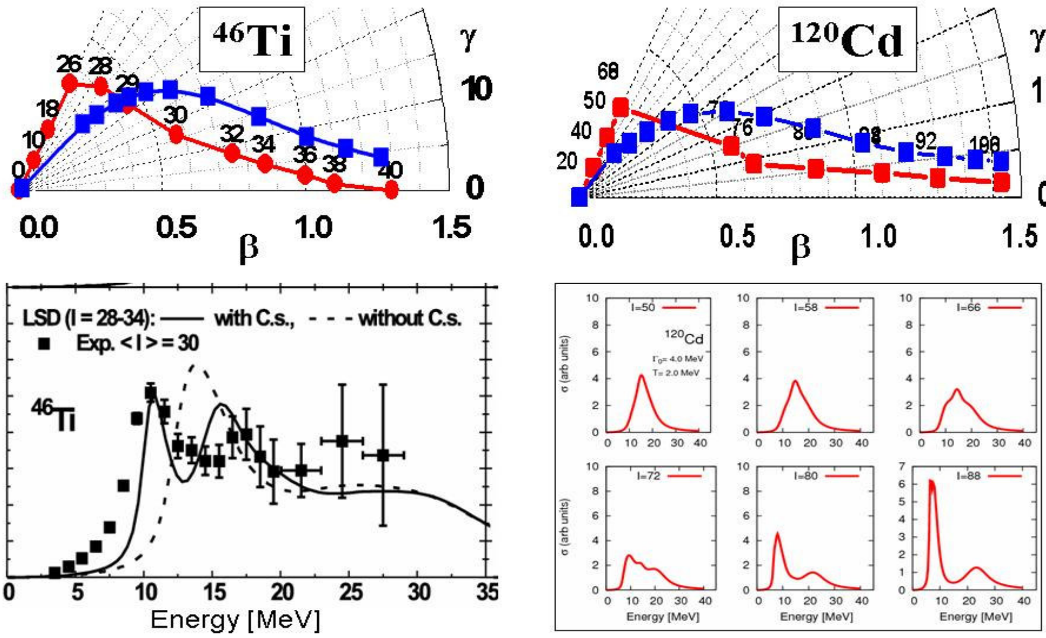

Fig. 1) Upper row: The predicted evolution of the equilibrium (red) and average deformation (blue) with angular momentum for ^{46}Ti and ^{120}Cd. Lower row: left) experimental and theoretical GDR strength functions for ^{46}Ti at very high spins; right) predicted GDR strength functions for ^{120}Cd at spins I = 50, 58, 66, 72, 80 and 88 ℏ.

The difficulty inherent to the experimental study of these phenomena is related to the very wide spin window covered by the oblate-triaxial Jacobi shape change and the proximity of the fission limit. Favourable conditions are expected to be met in exotic, neutron-rich nuclei, accessible via fusion-evaporation with the advent of SPIRAL2 beams. As an example, we consider the compound nucleus ^{120}Cd (Fig. 1) which can be produced at very high angular momentum, almost reaching 100 ℏ, in inverse kinematics by the SPIRAL2 ^{94}Kr beam impinging on ^{26}Mg. Several other nuclei predicted to exhibit a Jacobi transition either will be

[3] M. Kicińska-Habior et al., *Phys. Lett.* **B308** (1993) 225
[4] A. Maj et al., *Nucl. Phys.* **A73**1 (2004) 319; M. Kmiecik et al., *Acta Phys. Pol.* **B36** (2005) 1169
[5] D. Ward et al., *Phys. Rev.* **C66** (2002) 024317-1
[6] G. Benzoni et al., *Phys. Lett.* **540B** (2002) 199

within reach by the use of radioactive beams (^{98}Mo via ^{68}Ni + ^{30}Si or ^{71}Zn via ^{23}N + ^{48}Ca), or are already accessible with stable beams (^{98}Cd via ^{40}Ca+^{58}Ni or ^{44}Ti via ^{12}C+^{32}S). Such experiments can be performed by coupling high-energy γ-ray detectors with an efficient multiplicity filter. Experiments dedicated more specifically to finding correlations between the low-energy GDR component and superdeformed, or possible hyperdeformed, structures in residual nuclei are discussed in another LoI[7].

Another aspect related to the Jacobi shape transition in light nuclei is that the evaporation process evolves mainly via light charged particle (LCP) emission. As the LCP energy and the angular distributions are sensitive to the nuclear deformation of both the parent and daughter nuclei along the evaporation cascade, LCP detection constitutes a good tool for investigating the onset of very elongated shapes. The unequivocal proof of Jacobi shapes in hot compound nuclei and deformation of the successive evaporation residues hence calls for the simultaneous measurement of the γ-GDR decay and the angular distribution of charged particles. Coupling the INDRA array with a high-energy γ-array could achieve such a goal.

b) <u>Studies of shape phase diagrams of hot nuclei – GDR differential methods</u> (contact: A. Maj, I. Mazumdar)

Most nuclei are characterized by intrinsically deformed ground-state shapes caused by quantum shell effects. In the absence of rotation, thermal excitations wash out shell effects above a critical temperature and the equilibrium shape of the non-rotating nucleus is spherical. For a rotating nucleus, one generally expects a non-collective oblate (i.e. rotating around the symmetry axis) shape. However, theoretical calculations of A.L. Goodman[8] predict that many nuclei (mostly in the A=170-200 region) possess a temperature interval where rotation generates a prolate spheroid rotating along its symmetry axis: this is the non-collective prolate rotation, in contrast to that caused by the Jacobi transition described above. In such nuclei, a second critical temperature exists, above which the nucleus takes on a non-collective oblate shape. These critical temperatures are spin- and presumably also isospin-dependent. One expects also the existence in the temperature-spin diagram of a tri-critical point, around which non-collective oblate, non-collective prolate, and collective triaxial or oblate shapes coexist.

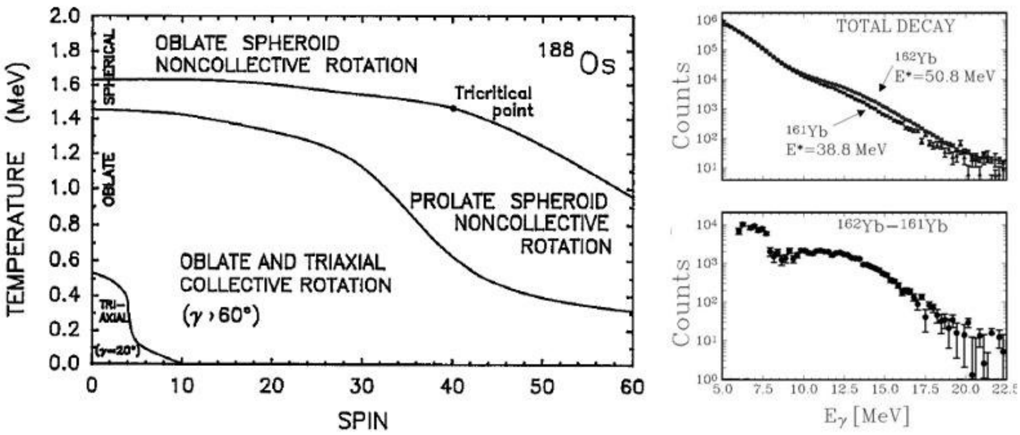

Fig. 2) Left: Phase diagram for ^{188}Os. Right: Illustration of the energy differential GDR measurement.

7 S. Leoni et al. "Collective modes in continuum" in LoI 'High-resolution Gamma-ray Spectroscopy at SPIRAL2' by W. Korten et al.

8 A.L. Goodman, *Nucl. Phys.* **A687** (2001) 206c

To explore these theoretical predictions of shape phase space transitions the differential (both in energy and spin) techniques[9] of the GDR measurement has to be employed in order to select small regions in the temperature-spin diagram. In fusion reactions involving radioactive beams of limited intensity, the applicability of the latter technique needs a very efficient array to measure the GDR γ-decay. Possible reactions will employ the SPIRAL2 high intensity Xe-beams (with A=138-145) on ^{48}Ti target (to produce $^{186-193}$Os compound nuclei) and ^{52}Cr target (to produce $^{190-197}$Pt compound nuclei).

c) Hot GDR studies in neutron rich nuclei (contact: D.R. Chakrabarty, M. Kmiecik)
We propose to study nuclear structure at finite temperature and angular momentum in neutron rich nuclei by measuring high energy gamma rays deexciting the GDR in hot nuclei. Most experiments involve heavy-ion fusion reactions with stable beams that produce proton rich or nearly stable compounds. A few of these measurements reported on the importance of disentangling temperature T and spin J influences on the GDR width. The thermal shape fluctuation model[10] has been found to be very useful in explaining the T and J dependence although many discrepancies exist. SPIRAL2 beams at energies of typically 5 to 10 A MeV provide a unique opportunity for extending these studies to neutron rich species. Hot GDR studies on neutron rich nuclei are crucial for going further, keeping in mind that, in addition, the GDR strength function may change when going towards more neutron rich systems – e.g. soft dipole modes can emerge.
As an interesting starting point we mention a scenario in which a ^{132}Sn beam bombards ^{12}C producing the compound nucleus ^{144}Ba. The latter has 6 more neutrons than the heaviest stable Ba isotope. At a beam energy of 5.7 A MeV, accounting for energy loss in e.g. a 1 mg/cm^2 thick ^{12}C or a 1.4 mg/cm^2 thick ^{7}Li target leaves a *CN* with a mean excitation energy of 55 and 43 MeV, respectively, with a spread of ±5%. The maximum angular momenta populated will be 30 $\hbar$ and 20 $\hbar$, respectively, while temperatures are in the range of 1.2-1.3 MeV. The advent of SPIRAL2 will allow a detailed study of the chain of Ba isotopes along which various ground state deformation are present. Radioactive Sn beams on ^{12,13}C targets will produce neutron rich Ba species (A=139-145) while the proton rich and stable isotopes (A=124-137) are accessible with ^{12,13}C beams on stable Sn targets.

d) Isospin mixing at finite temperature (contact: M. Kicińska-Habior)
As far as the measurement of isospin mixing in highly excited N=Z nuclei is concerned, a number of systems have been investigated so far, and the expected trend of decreasing mixing at higher temperature has been observed[11]. This effect is studied by measuring the hindrance of E1 emission in T=0 nuclei produced when two T=0, N=Z nuclei fuse. The GDR yield of this self-conjugate system is compared to that in a nearby N≠Z nucleus. The isospin mixing coefficient is extracted using a statistical model. Mixing coefficients α^2 between 0.5 and 0.02 have been measured so far in the temperature range from 1.5 to 3.5 MeV. Nuclei have been studied in the mass range from A < 30 to A=60. As already mentioned, a decrease of the mixing coefficient α^2 at increasing temperature has already been measured, while there are hints of an increasing trend going towards heavier systems. The future availability of radioactive beams will make it possible to study heavier N=Z systems such as ^{68}Se

[9] A. Maj et al., *Phys. Lett.* **291B**, (1992) 385; I. Mazumdar et al., *Nucl. Phys.* **A731** (2004)146
[10] W.E. Ormand, P.F. Bortignon, R.A. Broglia, *Nucl. Phys.* **A618** (1997) 20; N. Dubray, J. Dudek, A. Maj, *Acta Phys. Pol*. **B36** (2005) 1161; and references therein
[11] M.N. Harakeh, et al., *Phys. Lett.* **B 176** (1986) 297; J. A. Behr, et al., *Phys. Rev. Lett.* **70** (1993) 3201; M. Kicińska-Habior, *Acta Phys. Pol.* **B 36** 1133 (2005); E. Wójcik et al., *Acta Phys. Pol.* **B 37** (2006) 207

(^{44}Ti+^{24}Mg), ^{80}Zr (^{56}Ni+^{24}Mg), ^{84}Mo (^{72}Kr+^{12}C), ^{96}Cd (^{72}Kr+^{24}Mg) up to ^{100}Sn (^{72}Kr+^{28}Si), where the mixing is expected to reach the largest values (α^2 ~0.5).

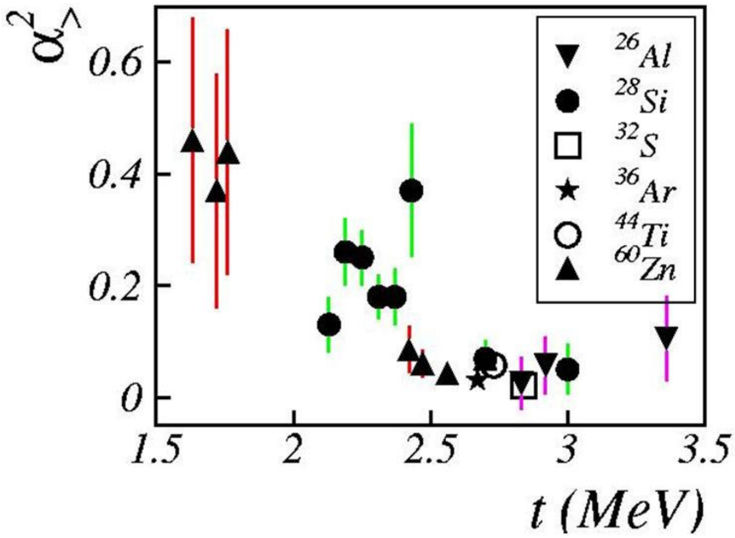

Fig. 3) Measured isospin mixing coefficients for different nuclei as a function of temperature. The expected decrease in mixing is observed.

e) Onset of the multifragmentation and the GDR (contact: J.P. Wieleczko)

The study of nuclei under extreme conditions, especially the question about the highest excitation energy a nucleus can sustain has driven a large number of investigations. The properties of excited nuclei have been widely studied by means of two independent probes: the temperature dependence of collective modes such as the Giant Dipole Resonance, the fate of the compound nucleus picture and the onset of the multifragmentation process, i.e. the simultaneous breaking of a nuclear system into several pieces of intermediate masses.

It has been suggested that hot GDR is a good indicator of the cohesion of an excited system. Conversely, the disappearance of the GDR might be considered as a signature of a transition towards a chaotic regime[12]. A strongly debated feature is the saturation or the decrease of the GDR yields as the excitation energy increases. From the accumulated data, it has been shown that the limiting excitation energy for collective motion is around 5 A MeV for compound nuclei of mass A=60-70 and about 2.5-3 A MeV for A=110. Those values are surprisingly close to the limiting temperature extracted from multifragmentation studies on the liquid-gas phase transition in excited systems. Multifragmentation is a very common disintegration mechanism of hot nuclei produced in heavy-ion induced reactions. Its threshold has been evaluated at excitation energies around 2-3 A MeV (temperature close to 5 MeV) by numerous studies performed in large collaborations using powerful 4πLCP arrays such as DELF, AMPHORA, MiniBall, ISIS, ALADIN, EOS and INDRA. For example, a systematic study of caloric curves allows the temperature (or conversely the excitation energy) to be extracted at which the caloric curve starts to deviate from the standard Fermi gas behaviour and develops a "plateau" or a "kink". These limiting temperatures are of the same order of magnitude as those deduced from GDR studies. Combining both of sets of data (see Fig. 4), it seems that the loss of collective motion and the gradual disappearance of the GDR could be linked to the appearance of a new fragmentation mode such as multifragmentation. It is worth noticing that up to now, no attempt has been made to establish a firm correspondence between both signatures. This section deals with the issue of whether such a link exists.

[12] P. Chomaz, AIP Conference Proceedings, April 2002, Volume 610, Issue 1 , p. 167

The limiting temperatures deduced from the caloric curve have been determined for a wide range of masses, while data on the limiting temperatures of the collective motion and the hot GDR cover a restricted range and nothing firm is established above A=120 on the demise of collective motion. This lack of data for heavy nuclei is worth noticing, since finite size and Coulomb effects play a major role in both collective modes and instabilities.

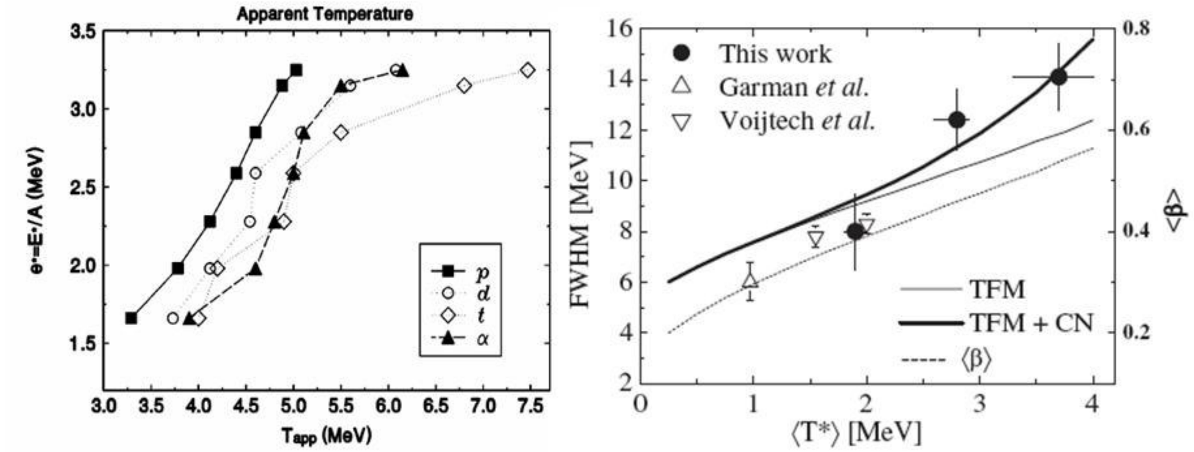

Fig. 4) Left: Experimental excitation energy per nucleon e* versus apparent temperature T_{app} for p, d, t, α measured in the ^{28}Si+^{100}Mo at 700 MeV[13]. Right: GDR width as a function of the temperature measured in the reactions ^{64}Ni+^{68}Zn at 300, 400, 500 MeV[14]. Both figures indicate the need of high energy gamma ray measurements at the excitation energy where a plateau has been observed in the apparent temperature.

We intend to measure high-energy γ-rays and charged products simultaneously. This will require coupling a very efficient high-energy γ-rays detector with a powerful charged particle array. We plan to first perform a series of experiments using GANIL beams and the INDRA setup coupled to the new gamma-calorimeter. Two mass regions are suggested for exploration: A=120-140 (Ni+Zn) and A=180-200 (Mo+Mo or Xe+Sn). The investigations will be further extended to SPIRAL2 beams, where isospin effects on the onset of multifragmentation can, in addition, be studied. Beams can then be chosen which allow the same compound nucleus to be formed from entrance channels having different N/Z e.g. ^{64}Ni+^{80}Zn, ^{94}Kr+^{50}Ti, ^{96}Sr+^{48}Ca leading to ^{144}Ce; ^{122}Cd+^{58}Ni, ^{90}Kr +^{90}Zr. The beam selection is dictated by experience of the necessary intensity for such studies. This programme could be done either with INDRA or new apparatus, currently being developed, such as FAZIA.

It should be recognised that this program could be started today using the existing tools (INDRA and Chateau de Crystal for example) at GANIL by studying the reaction ^{64}Ni + ^{68}Zn at energies up to 12 A MeV (corresponding to 2.5 A MeV of excitation energy in the compound nuclei). This reaction has been studied at Legnaro at energies up to 8 A MeV without observing a saturation of the width of the GDR. Such an experiment could therefore be considered as a test experiment with stable beam.

A second strategy could be to run two experiments in parallel: one with the charged particle and a residue (being the trigger), and a second experiment with a gamma-calorimeter and the same trigger as above. These plans are very feasible and do not demand major effort in simulations.

[13] A. Chbihi et al., *EPJA* **5** (1999) 251

[14] O. Wieland et al., *PRL* **97** (2006) 012501

f) Reaction dynamics by means of γ-ray measurements (contact: Ch. Schmitt, O. Dorvaux)

i) Viscosity in nuclear matter

The dynamical evolution of an excited nucleus is commonly explained by transport theories which distinguish collective and intrinsic degrees of freedom. Nuclear viscosity leads to a transfer of energy from the collective motion into intrinsic temperature. Due to the variety of shapes, excitation energies E^* and angular momenta L explored by the system along its decay, no consensus emerges yet about the dissipation strength β. Theoreticians do not agree neither: Does viscosity stem from the interaction of the nucleons with the moving boundaries of the system and/or from individual nucleon-nucleon collisions? The manifestation of friction on the temporal evolution of a fissioning system is three-fold[15]. In addition to the Kramer's reduction factor of the Bohr and Wheeler transition-state-model prediction, caused by the stochastic nature of dissipation, viscosity slows the collective motion down. That results in a transient time τ_{trans} until which quasi-equilibrium is established at the fission barrier and an additional delay τ_{ss} along the saddle-to-scission descent. Experimentally, time scales are commonly inferred using particle and γ-ray clocks[16]. Compensation effects and uncertain parameters still make the conclusion controversial. The influence of the primary fusion stage might also be critical: the actual compound specie left after fusion can be quite different in shape, E^* and L from that taken as the initial compound nucleus (*CN*) in the fission analysis. These initial conditions affect the duration of τ_{trans}[17]. It has been shown that fission σ_f, or equivalently evaporation residue σ_{ER}, cross sections give insight into to the early stage of the process and the possibility to determine β via τ_{trans}. These effects become increasingly important with *CN* mass.

The knowledge of the high-spin behaviour, the variation with L of the moment of inertia and the fission barrier is essential to estimate shell-correction energies. The knowledge of the entry (E^*, L) point constrains the calculations by providing the appropriate initial conditions. Further, it allows the influence of E^* and L on dissipation to be determined. The variety of SPIRAL2 beams helps to better investigate the interplay of entrance-channel dynamics since, for a given *CN*, E^* and L can be varied independently. The entry (E^*, L) point can be obtained by measuring the γ-ray multiplicity M_γ and energy sum E_γ in coincidence with evaporation residues[18].

ii) Fusion - Quasi-Fission competition

In heavy-ion collisions, capture by nuclear attraction is not necessarily followed by fusion. Instead, the intermediate di-nuclear system along its trajectory on the potential energy landscape can re-separate due to Coulomb repulsion before achieving complete amalgamation into a *CN*. The resulting binary fragmentation is denominated quasi-fission (QF). Studying the competition between fusion and QF usually consists of investigating the competition between fission after *CN* formation (CNF) and QF. So far, most of the information relies on fission fragment masses, energies, anisotropies and neutron multiplicities. Most certainly, CNF and QF differ in time and in the amount of initial kinetic energy dissipated (see Fig. 5 left part). Even if the product of projectile and target charges $Z_P \cdot Z_T$ continues to serve as a crude ordering parameter, the influences of excitation energy, angular momentum, nuclear structure and the shape at contact play a decisive role in defining QF onset[19].

[15] K.H. Bhatt et al., *PRC* ***33*** (1986) 954
[16] D.J. Hinde et al., *NPA* ***502*** (1989) 452c and M. Thoennesseen et al., *PRL* ***59*** (1987) 2860
[17] R.J. Charity, arXiv:nucl-th/0406040v1 (2004)
[18] M.L. Halbert et al., *PRC* ***40*** (1989) 2558
[19] M. Dasgupta, *NPA* ***734*** (2004) 148 and references therein

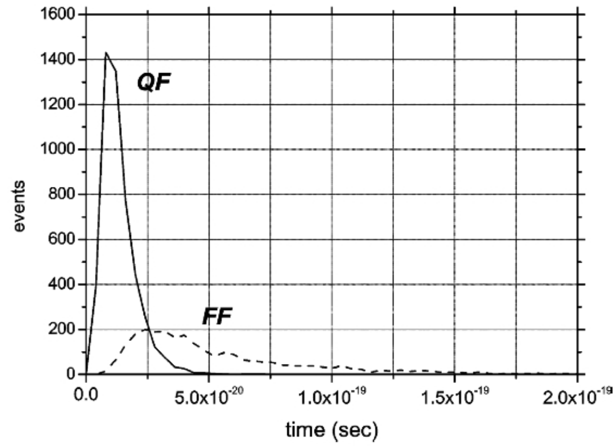

Fig. 5) Left: The distribution of travelling time in the reaction 58Ni+208Pb at E*=185.9 MeV for the Quasi-Fission (QF) and Fusion-Fission (FF) processes (from [20]). Right : Fusion-fission times obtained by neutron (full circles) and GDR (open circle) measurements (from [21]).

SPIRAL2 beams will allow us to deepen our understanding of the fusion-QF dynamics with lighter symmetric entrance channels leading to actinide compound nuclei. The cross sections are larger than in the super-heavy element region where QF is predominant. Knowledge of M_γ and E_γ should give an insight into the characteristics of the system at scission in E^*, L and shape. The influence of these parameters on fusion-QF competition[22] can then be investigated. Furthermore, since the GDR energy depends on the size and deformation of the emitter, the GDR of the *CN* has a different energy from that emitted by the di-nuclear system leading to QF[23]. The analysis of the γ–GDR component from the decay of the fissioning system and from the decay of the fission fragments using the statistical model, may thus probe the distortion of a long-lived system. More, the extracted time from the γ-GDR component differs from neutron measurements (see Fig. 5 right part). This discrepancy is still not well understood and strengthens the necessity to obtain more γ-GDR data.

g) <u>Heavy ion radiative capture</u> (contact: S. Courtin, D.G. Jenkins)

Heavy ion radiative capture is a rare process due to the high Coulomb barriers and overwhelming competition from particle emission. There are only a few examples where such a process is known to exist. A particularly successful program of measurements over the last five years has been pursued by the York and Strasbourg groups led by David Jenkins and Florent Haas/Sandrine Courtin, respectively. The focus of the York group was initially on the $^{12}C(^{12}C,\gamma)$ reaction. Early studies of this reaction at Brookhaven in the 1980's had indicated a series of resonances for radiative capture to the ground state and first few low-lying states in ^{24}Mg[24]. These studies were carried out using a single large NaI detector. Piling-up of low energy gamma rays from the dominant particle evaporation channels in the single crystal detector prevented the observation of capture to high lying states in ^{24}Mg. It was speculated that such states might form the doorway between the entry capture resonance, with its molecular ^{12}C-^{12}C structure and the deformed ground state of ^{24}Mg. Such doorway states

[20] Y. Aritomo et al., *NPA* **759** (2005) 309
[21] P. Paul et M. Thoennessen, *Annu. Rev. Part. Sci.* **44** (1994) 65
[22] A.Yu. Chizhov et al., *PRC* ***67*** (2003) R011603
[23] R. Butsch et al., *PRC* ***44*** (1991) 1515
[24] A.M. Sandorfi, Treatise on Heavy-Ion Science Vol. 2 Sec. 3, Plenum Press, New-York, 1985, and ref. therein

might be associated with long-predicted highly deformed rotational structures in ^{24}Mg whose bandheads lie at an excitation energy of around 10 MeV. Studies have been carried out at Argonne National Laboratory using the Fragment Mass Analyser to demonstrate that the ^{12}C(^{12}C,γ) capture cross-section was significantly larger than earlier believed. Once this had been shown, further measurements were made using Gammasphere at Lawrence Berkeley National Laboratory. These demonstrated that the capture process was also mediated through a number of states around 10 MeV in ^{24}Mg but the detection efficiency was too low to identify the specific states involved, nor was it possible to detect the previously known capture transitions to the low lying states which have energies of around 20 MeV[25]. A further series of measurements was then carried out using the DRAGON recoil separator at TRIUMF in conjunction with its target BGO array. This, in principle, allowed all capture pathways to be measured. It did not prove straightforward to extract the information of interest, however, since the acceptance of the separator was not large enough to accept all capture residues, and the unusual geometry of the BGO array made it essentially impossible to obtain reliable gamma ray angular distributions. The Strasbourg-York group is also investigating the ^{12}C(^{16}O,γ) radiative capture reaction. The system had been explored by Sandorfi et al. in the 1980s, showing that the capture cross-section exhibit narrow resonances, measuring nevertheless only the decay of those resonances to low lying states of the compound ^{28}Si nucleus as for the ^{12}C+^{12}C system. We have revisited this reaction recently at TRIUMF using the Dragon separator to measure eventual doorway states and measured the branching ratio to them. The analysis of the experiment is under progress but doorway states have already been identified to lie around 12 MeV[26]. It is important to note that cluster bands have been predicted in ^{28}Si having a ^{12}C-^{16}O structure by Ohkubo and Yamashita and that the observed γ-rays could be interpreted as links between those bands.

[25] D.G. Jenkins et al., *Phys. Rev.* **C71** (2005) 04301
[26] S. Courtin et al., Fusion 06, *AIP Conference Proceedings* **853** (2006) 134

Methodology (Typically 2-3 pages)

<u>Beam properties</u> *(primary beam, RIB: nature, intensity, time resolution, purity, use of beam tracking detectors etc. - to be specified if possible):*
For all the above studies good beam quality is important. In particular, to accurately track down isospin effects calls for a high purity at the 10^{-4} level. The energy resolution presently provided by the CIME cyclotron should be well suited.
The topics outlined in this LoI will profit from both stable and radioactive beams, especially from the large variety of neutron-rich and neutron-deficient (N=Z) beams. We are here mainly concerned with both the light and the heavy fission-fragment SPIRAL2 beams with energies ranging from 4 A MeV up to 12 A MeV. An intensity of 10^5 to 10^9 pps for prompt studies and up to 10^{14} pps for focal plane experiments would be appropriate. The beam structure is rather important, e.g a time resolution of 1 ns is needed for recoil separator experiments. The dimensions of the beam halo is crucial for prompt experiments - a relatively small, at most 5x5 mm^2, spot on the target is required.

<u>Target(s)</u>
RIB production target:
In addition to the UC_x target for the production of fission-fragment beams, we strongly support the construction of a second target station to produce RIBs in heavy-ion and light-ion induced reactions on other target materials using the ISOL technique, in particular to produce proton-rich and intense light-ion beams.

Secondary targets:
Typical secondary targets will be metallic foils with a thickness of ca. 0.5-3.0 mg/cm^2. For some reaction dynamics studies, the use of actinide radioactive targets will be requested.

<u>Instrumentation and detectors</u> *(equipment to be constructed or modified):*

The scientific program discussed here requires the simultaneous measurement of several observables with the highest possible efficiency: i) high energy γ-rays, ii) γ-multiplicity/sum-energy information, iii) reaction product (recoil or fission fragments) selection and iv) charged particle spectroscopy.
Below is listed the specific instrumentation required for each physics case.

Physics case a)
In this case, the requirements are a calorimeter for high energy gamma rays (ranging from 3 up to ca. 40 MeV), a highly granular multiplicity and sum-energy detector (for gamma energies from 100 keV up to 3 MeV), an efficient charged particle spectrometer and a recoil detection system. In specific cases, it might be useful to couple the high-energy calorimeter and the multiplicity filter, with EXOGAM, the AGATA demonstrator or the AGATA 2π phase.

Physics cases b), c) and d)

The measurement of the relevant high energy gamma spectra (especially when using differential techniques) needs high efficiency, large volume gamma detectors because the gamma decay width represents a small fraction, less than 1%, of the total particle decay width. Neutron-induced events can be discriminated by a time of flight (TOF) measurement, while cosmic ray events may be reduced both with active (a detector in anti-coincidence mode around the main detector) and passive (lead) shielding. Pulse pileup and summing effects have to be eliminated and, a proper Doppler correction, especially in inverse kinematics experiments, is mandatory.

In a typical experimental configuration, high-energy gamma rays would be detected in BaF_2 detector arrays or any other high efficiency calorimeter. The angular size of each detector element should not be too high in order to restrict Doppler broadening. Fusion-like residues should be detected in the forward direction to discriminate against gamma rays coming from any non-fusion like events. Inverse kinematics has the advantage that the residue nuclei come out of the target. On the other hand, the proximity of the compound nuclear mass and energy to those of the projectile makes the situation a little challenging. Finally, a multiplicity detector array will be put near the target to have angular momentum gating.

Physics case f)

A calorimeter that can handle multiplicities around $M_\gamma \sim$ 1-20, energies E_γ from 100 keV up to 20 MeV, and counting rates of about 10^4-10^5 Hz is required. Its efficiency (~25% at 1.3 MeV - a few % at 20 MeV) and timing characteristics (desired 1 ns resolution) are most important and call for a rather highly segmented device. A reasonable energy resolution (3%) can help to unambiguously identify the fission products depending on the capabilities of the detector coupled to that purpose with the calorimeter. This latter point besides calls high modularity

Physics case g)

The extension of the work described above would benefit greatly from access to a highly-segmented array of next generation scintillator material showing a good resolution (2-3 %). The gamma rays of interest are in the energy range 1-25 MeV. The mean gamma multiplicity for such events is two. It would be beneficial for the device to be symmetrical and uniform so that angular distributions of gamma rays could be obtained. The device could be operated with or without an associated recoil separator. It is not clear that a recoil separator would be necessary if the scintillator ball formed essentially a 4 pi calorimeter, since the capture channel could be selected by requiring that all of the energy emitted as capture gamma rays is recorded in an event. This separation will work in all of the cases of interest since the Q-value for radiative capture is generally large and positive.

According to the request shared by the above physics cases, the present proposal is intended to develop a **versatile γ-calorimeter** which dynamical properties match the wide physics range available at SPIRAL2. The device will need to be able to handle gamma-ray energies from 100 keV up to 40 MeV, multiplicities, $M\gamma$ from 1 to 30 and counting rates of about 10^4-10^5 Hz. The efficiency (>25% at 1.3 MeV, ~5% at 20 MeV) and timing characteristics (desired 1 ns resolution, to separate γ and neutron induced events) are very important and argue in favour of a highly segmented device. A solid angle coverage of as close as possible to 4π would, of course, be the best solution given the variety of the uses intended. In order to be flexible, this 4π device, it has to be possible to easily convert to a 2π or 1π geometry.

For most of the Physics cases discussed, it will be important to be able to operate in conjunction with ancillary detectors. Neutron and LCP detection, as well as reaction mechanism tagging are particularly important. The latter requires the selection of the heavy product (recoil or fission fragments). Use of the highly efficient INDRA charged-particle spectrometer is envisaged. For neutron detection, some detectors which already exist, such as DEMON, may be used. A R&D program aiming to develop a new scintillating material based on polymerization which is sensitive to neutrons is still in progress. Our studies would obviously benefit from such material when it becomes available. As far as evaporation recoils are concerned, depending of the kinematics, the wide acceptance VAMOS separator or the Krakow Recoil Filter Detector could be coupled to the calorimeter. The information they provide is, in any case, crucial for proper Doppler correction. Where fission is of interest, the coincident fragments can be detected (and their mass roughly determined) by micro-channel plates or multi-wires proportional counters. Last but not least, an accurate channel selection and/or additional γ-spectroscopy information can be obtained using the 2π AGATA sub-array (or part of it). All of these considerations clearly call for a highly modular calorimeter.

A clear plan for such a new gamma-calorimeter can only arise from an intensive R&D program, with GEANT4 simulations being a key component of this work (Some of the participating institutions have already begun work on this aspect). A number of scenarios are presently under consideration:

a) Develop and construct a completely new calorimeter, which can measure both high energy and low energy gammas. This can be done either simultaneously (using signal pulse processing), or by selecting one range or another (inserting/removing absorbers in front and changing the dynamical range).

b) Develop a 2-shell calorimeter ("γ-telescope"): inner (hemi-)sphere, highly granular, made of new short crystals ($LaBr_3$(Ce), $LaCl_3$, CeZnTe). For instance a 1" x 1" cylindrical $LaBr_3$(Ce) crystal offers a good resolution (2.8% at 667 keV), a fast emission (26ns) - rather good for timing measurements, and a high linearity over a wide temperature range. The readout might be performed with APDs or with digital electronics which would offer the possibility of pulse shape analysis. The outer (hemi-)sphere, with small granularity but with high volume detectors, could be made from conventional crystals (preferably of BaF_2), or using existing detectors (Chateau de Crystal or HECTOR). The inner-sphere will be used as a multiplicity filter, sum-energy detector and will also serve as an absorber for the large detectors behind. The outer-sphere will measure high-energy photons.

c) Use existing high-energy gamma detectors (e.g. Chateau de Crystal) and fill the remaining solid angle with a new calorimeter.

Pair-production is a very important process for high energy gamma rays. This dictates that, the crystal sizes should be large enough to absorb the 511 keV photon scattered from the neighbouring crystals, while small enough to let the 511 keV gamma ray escape the crystal where the pair production take place. This would also give the unique opportunity to use the calorimeter as a *pair-spectrometer array* to study γ-rays with energies higher than 1022 keV - in practice, those higher than 3 MeV.

We anticipate that the R&D phase could be performed in synergy with the EXL-R3B and HISPEC/DESPEC collaborations within NUSTAR@FAIR community. They will also be investigating new materials such as $LaCr_3$ and $LaBr_3$, and several photomultipliers and APDs, The R&D should be completed by 2008.

The Recoil Filter Detector (RFD) is an ancillary detector for a germanium detector array, developed for in-beam γ-spectroscopy investigations of nuclei produced in fusion-evaporation reactions. The RFD selects evaporation residues from other reaction products with a total efficiency of 20% - 50% and measures precisely their velocity vectors in coincidence with γ-rays. This technique strongly suppresses background coming from other reaction channels in the filtered γ-spectrum and leads to a significant reduction of the Doppler broadening of the γ-line width, thus improving thus the energy resolution. The RFD was used successfully with the EUROBALL IV (EB) array in several experiments at the VIVITRON accelerator in the Institut de Recherches Subatomiques (Strasbourg).

INDRA
The multidetector INDRA is made of 336 detection cells arranged in 17 rings; the first one (2°-3°) is an array of 12 plastic scintillators. Rings 2 to 9 (polar angle from 3° to 45°) consist in three layers comprising an ionization camber (IoCh) followed by a solid state Silicon detector (Si) and a Cesium Iodide scintillator (CsI(Tl)). The medium and backward angular range (45° to 176°) are covered with IoCh/CsI ensembles. The device provides a 90% of 4π geometrical efficiency, charge identification from H to Z=60, and a mass resolution up to Beryllium is achieved up to 200 A MeV. The identification threshold is about E/A= 0.7 MeV (respectively 1.4 MeV and 1.7 MeV) for fragments with charge Z=3 (respectively Z=25 and Z=50). The multidetector INDRA is presently installed at GANIL.

Château de Crystal
The Château de Crystal is an array composed of 74 BaF_2 scintillators. The shape of each element is hexagonal with a length of 14 cm and 9cm side. The photo peak efficiency (energy resolution-FWHM) measured using standard sources are 48.7% (22.9%) at 344 keV, 35,6% (14.2%) at 779 keV and 26.1 (11.8%) at 1.33 MeV. It is a large and very compact array covering 84% of 4π. The granularity is good which allows to control the Doppler shift for photons emitted from high velocity source. Such an array has been widely used at the VIVITRON accelerator, and it is now installed at GANIL.

DEMON
DEMON[27] is the acronym for MOdular Neutron DEtector. It is composed of 100 NE213 liquid scintillator detectors of 16 cm diameter and 20 cm long. It is a highly modular setup, with an excellent n-γ discrimination and very high intrinsic efficiency (70% at 2 MeV and remains at 50% at 10 MeV). The neutron energy is obtained by a time-of-flight measurement (resolution of ~1.2 ns) and the n-γ discrimination is based on the total and slow components of the signal using VXI electronics.

[27] S. Mouatassim et al., *NIM* **A359** (1995) 530 ; CRN Report 94-40 (1994).

Theoretical support *(short description of the necessary calculations and developments):*

i) GDR properties, shape transitions and thermal shape fluctuations

Theoretical interpretation of the Giant Dipole Resonances in nuclei requires simultaneously taking into account thermal excitations, the large deformation spaces and fast rotation (high spin states). All these mechanisms lead to predictions of the deformation splitting of the giant dipole profile function into two- (axial shapes) and into three-peak profiles, the latter in the case of the tri-axial nuclear shapes. Moreover, in the case of fast rotation about one of the principal axes of the nucleus, an additional splitting of the giant-dipole profile into five peaks is predicted with sizeable separation of the various peaks - especially pronounced for the light nuclei.

Successful predictions/interpretation of the first experimental results related to the Coriolis splitting of the giant dipole resonances has been obtained by employing the latest version of the macroscopic nuclear energy expression, taking into account the curvature contributions to the total nuclear energy. This macroscopic limit provides a realistic description of the nuclear conditions in the temperature range roughly from 1 to 3 MeV; the corresponding method is known under the acronym LSD (Lublin-Strasbourg Drop) approach to modeling of the nuclear energy in terms of the spin and deformation. This approach has led to a rather successful description of the thermal fluctuations necessary in order to take into account the nuclear shape evolution accompanying the giant dipole phenomenon (population and decay).

This new LSD approach has been successful in the first large scale predictions of the so-called Jacobi transitions at high spins - phenomenon consisting in the dramatic shape transitions in function of increasing spin from the moderately deformed oblate shapes to the large prolate deformation evolving through the sequence of triaxial shapes within a narrow energy window of a few units of spin only. The corresponding formalism has been elaborated using computer codes developed by the Strasbourg theory group. It has been used within the Cracow-Strasbourg collaboration leading to a number of publications.

ii) Isopin mixing

In nuclei in the ground state, the dependence of the isospin mixing on the mass number A and the atomic number Z was predicted. It may be expected that it should occur also in highly excited nuclei. We have calculated isospin mixing probability at high excitation in self-conjugate nuclei using the formula:

$$\alpha_>^2 = \frac{\Gamma_>^{\downarrow}/\Gamma_>}{1+\Gamma_>^{\downarrow}/\Gamma_> + \Gamma_<^{\downarrow}/\Gamma_<},$$

According to the theoretical predictions and in agreement with our findings the isospin mixing spreading width $\Gamma_>^{\downarrow}$ should not change much with the excitation energy and mass of the compound nucleus. The total decay width $\Gamma_>$ and $\Gamma_<$ calculated for different compound nuclei at the same excitation energy decrease with mass number of the excited compound nucleus. Thus we may expect that the isospin mixing probability extracted for nuclei at the same excitation will increase with mass number A. It would be interesting to check such a trend for nuclei heavier then mass A= 60. It would also be worthwhile to study further the temperature dependence of isospin mixing in heavier nuclei, especially for well defined nuclear temperature.

iii) Multifragmentation onset

The description of a transition from a 'semi-quantal regime' at low excitation energies, dominated by the collective excitations (the giant resonances) and n/p cooling, to a 'statistical regime', dominated by the (multi-)fragmentation mechanism, is a challenge for a nuclear theory. Many theoretical approaches exist which are suited either to the semi-quantal regime or to the statistical regime but they cannot describe a gradual transition from one regime to another. The future development of hybrid models containing both mean-field dynamics, stochastic mechanism of evolution in the partition-space, and the heavy-fragment identification mechanism is mandatory. A natural starting point in this direction could be approaches based on the antisymmetrized molecular dynamics (AMD, FMD, ...) or on the stochastic mean-field (stochastic Schroedinger eq.). One should stress that we do not know yet the detailed mechanism of transition from ordered- (low excitation energies) to disordered- (higher excitation energies) phase of the fragmentation process. Hence, we do not know yet what kind of production mechanism of intermediate-size fragments should be simulated by those future hybrid models.

iv) Reaction dynamics

Within the three-stage scenario outlined in the text, the evaporation residue cross section reads:

$$\sigma_{ER} = \pi(\lambda/2\pi)^2 \cdot \Sigma_{l=0}^{\infty}(2l+1)\mathrm{T}_l \cdot P_{fus}(E^*,l) \cdot W_{sur}(E^*,l)$$

where T_l describes the transmission for the angular momentum wave l and λ is the de Broglie wavelength. The P_{fus} term determines the probability of *CN* formation in the competition with QF and W_{sur} is the survival probability of the *CN* against fission (i.e. CNF). The CNF cross section is given by an equation similar to (1) replacing W_{sur} with $(1-W_{sur})$. Transmission coefficients are reliably predicted within a realistic coupled-channel scheme near the barrier or according to the simpler (e.g. Bass or WKB) approximations at above barrier energies.

At high excitation energy, statistical evaporation calculations become tricky due the major role played by nuclear viscosity. By means of judiciously chosen asymmetric reactions, we can get rid of the complex interplay from QF (i.e. P_{fus}=1) and concentrate on the magnitude of dissipation that affects W_{sur} provided a realistic time-dependent fission-decay width is included in the evaporation calculation. The combination of stable and radioactive beams allows cross-measurements useful for setting remaining uncertain parameters. Furthermore, the knowledge of the *CN* entry (E^*, L) point should give insight into the temperature- and spin-dependence of friction.

At low excitation energy, the influence of dissipation on W_{sur} is weaker and we shall concentrate on fusion-QF dynamics. Thanks to SPIRAL2, this topic can be addressed with lighter, symmetric systems for which evaporation residue and CNF cross sections are more reasonable than in the super-heavy element (SHE) region where this issue is usually studied. The dynamical calculations dedicated to evaluate P_{fus} are restricted to semi-classical equations. A full Quantum mechanical description is crucially missing to date. Nonetheless, promising works are in progress. The advent of data involving lighter *CN*, whose analysis does not suffer from uncertain properties in the same was as the SHE interpretation, is crucial.

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

Extensive GEANT4 calculations are absolutely necessary to precisely define which scenario described above and geometry would be the most efficient one to fulfil the requests of so different physics cases. Some institutes (IPHC Strasbourg, IPN Lyon, IPN Orsay, IFJ PAN Krakow) having the required tools and expertise, have already declared an interest in carrying our such work. We estimate at least two years to design the geometry of such setup.
In parallel, some tests of new crystals would have to be performed and their characteristics fully described in association with different types of phototubes and electronics. A test bench can easily be carried out as soon as we have the funding to buy a new crystal of reasonable size. This task should take less than one year.
The existing and very modular setups already mentioned (Château de Crystal or HECTOR) should not request too much time to be associated with a new crystal ball. Of course, some CAD would be needed for the mechanics assembly (this can be done for example in IFJ PAN Krakow workshop).

The collaborating institutions, after this LoI is approved, are going to prepare and sign a Memorandum of Understanding. This MoU should be drawn up to allow the members of the collaboration to indicate their desire to work towards obtaining the funds necessary to finalise the design and building up of the gamma-calorimeter setup.
More details on the process leading to the signature of the Memorandum of Understanding will be given in the forthcoming full proposal, if the present LoI is recommended by SAC.

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

Since the geometry and the type of crystal is still not yet defined, a cost evaluation is necessarily rough. It is reasonable to expect that the quoted prices for the crystals will decline over time as the available size increases, and if a large order were made. On the basis of 600 $LaBr_3$ crystals (2.5 x 2.5 cm^2) to cover the first layer, in conjunction with a second layer made from existing detectors, we estimate 1,8 M€ would be needed to achieve the construction of a new calorimeter including electronics and DAQ.
The estimated manpower for the GEANT4 simulation is 12 physicists (including Ph.D. students) and 4 engineers and programmers for DAQ.