LETTER OF INTENT

The γ-decay of the GDR in excited states and charged particles as a probe for nuclear shapes, symmetries and reaction dynamics: experiments with GARFIELD and HECTOR

A. Bracco, F. Camera, O. Wieland at al. (University of Milano, Italy)
F.Gramegna et al. (LNL Legnaro, Italy)
A. Maj, M. Kmiecik et al. (IFJ PAN Krakow, Poland)
M. Bruno et al. (Bologna University, Italy)
G. Cassini et al. (Firenze University, Italy)
J.P. Wieleczko et al. (GANIL Caen, France)
C. Beck et al. (IPHC Strasbourg, France)

for the ***GARFIELD-HECTOR collaboration***
(Milano, LNL, Krakow, Bologna, Firenze, Trieste, GANIL, Strasbourg)

Contact person : Franco Camera (franco.camera@mi.infn.it)

The present letter of intent briefly describes the motivation for undertaking a campaign of measurements focusing on selective studies of the gamma decay of the Giant Dipole Resonance in excited states using the array GARFIELD coupled to the HECTOR array. The key and common feature of these experiments is the combined measurement of gamma-ray and charged particles, the latter essential to understand the reaction dynamics leading to the nuclear structure information. In addition a good selection of the fusion-evaporation channel will be made by measuring the heavy recoiling nuclei in coincidence with the different reaction products.

In fact, the combination of the HECTOR array (for the measurement of high-energy γ-rays) with the GARFIELD set-up (for the measurement of energy and multiplicity spectra of light charged particles at different angles) gives the unique opportunity to perform new and more exclusive measurements for the study of nuclear structure at finite temperature, the population of exotic shapes and for testing symmetries such as the isospin symmetry.

The plan is to submit at least 4 different proposals each one dealing with a different topic. They are:

- The measurement of the isospin mixing in heavy N=Z nuclei at temperature 2-3 MeV *(spokeperson: O.Wieland - Milano)*
- The measurement of the temperature dependence of the width of the GDR in the mass region A=80 and A=200 in the temperature windows 2-5 MeV *(spokseperson: F. Camera - Milano)*
- Search for the Jacobi shape transition in light nuclei *(spokesperson: A. Maj - Krakow)*
- Onset of the multifragmentation and the GDR *(spokeperson: J.P. Wieleczko - GANIL)*

A proposal relative to the first measurement of the isospin mixing in N=Z nuclei in the A=80 at temperature 2-3 MeV has been submitted together with this letter of intent. This is because the coupling of the two detection systems requires a sizable amount of work (both for the mechanics and the electronics) and therefore we are interested to have a general response on the entire program of this Letter of Intent program before investing human and financial resources in this project.

The attached proposal should be considered only in case of a positive reaction of the LNL PAC at least to a part of the proposed experimental program.

1) Isospin mixing in the N=Z nucleus ^{80}Zr at high temperature

The problem of the mixing of states with isospin $I \neq I_0$ in N≈Z nuclei, related to the isospin symmetry and its breaking by Coulomb interaction, has attracted renewed interest both, at zero and finite temperature. In particular, at high excitation energy, restoration of the isospin symmetry should occur. This is due to the fact that the isospin mixing probability is related to the ratio of the spreading width of the Isobaric Analog States (IAS) with the statistical decay width of the compound nucleus. While the spreading width of IAS is expected not to depend on temperature [1], the decay width of the compound nucleus is known to increase with temperature so that these two effects result in a decrease of the isospin mixing probability (see right panel of figure 1 in the isospin proposal). So far the temperature dependence of the isospin mixing has been extensively investigated in light nuclei ($30 < A < 60$) [2] using the γ decay of the GDR in compound nuclei. The data in this mass region are consistent with the predicted restoration of the isospin symmetry [3]. Starting from this result and keeping in mind that the statistical decay width is a well known quantity one can infer from the measurements at finite temperature the isospin mixing probability at zero temperature. Therefore the investigation of the isospin mixing at finite temperature is a tool for the study of the isospin mixing problem particularly for several medium mass nuclei with N=Z which are unstable and difficult to populate at zero temperature. Consequently, the study of the isospin mixing at finite temperature with the GDR decay for nuclei with increasing Z is expected to provide information on how the Coulomb interaction is affecting the spreading width of the Isobaric Analog States.

The experimental technique for the study of the isospin mixing requires the measurement of the γ decay of the GDR in a hot compound nucleus formed using two reactions. In the first reaction the compound nucleus is formed in a I=0 state, in the other in a $I \neq 0$ state. As E1 transitions in a I = 0 system are strongly inhibited because of the isovector nature of the E1 dipole, from the comparison of the high energy γ-rays yield in the two reactions it is possible to extract the isospin mixing coefficient.

The included proposal intends to measure, for the first time, the isospin mixing in ^{80}Zr nucleus. A zero temperature value of 3-4 % is expected (see left panel of figure 1 in the isospin proposal).

2) Study of the damping mechanisms of the Giant Dipole Resonance in highly excited nuclei in mass region A ≈ 90 and A ≈ 200

The investigation of the behavior of the GDR width as a function of temperature is one of the main topics in the study of nuclear structure at finite temperature [4]. By studying the damping width of the GDR built on excited states one can learn on the temperature dependence of the relaxation mechanisms of collective modes. The two main relaxation mechanisms giving rise to the measured damping width which have been identified are the collisional damping and the thermal large-amplitude fluctuations of the nuclear shape.

The phenomenon of collisional damping is essentially connected with the coupling of the giant modes with the quantal fluctuations of the nuclear surface. Various predictions of the collisional damping width exist. In ref [5], making use of the Vlasov equation, an increase of the width with temperature has been predicted. In contrast, using the time dependence density matrix and the surface coupling model respectively, it has been found that the collisional damping width is basically independent of temperature [6,7]. The same conclusion has been also recently obtained within the Thomas-Fermi approximation [8] for collisional integral and using realistic in medium cross sections.

The second important mechanism at work in the breaking of the strength of the GDR is the coupling of the vibration to the large amplitude fluctuations (shape fluctuations) of the nuclear surface which are induced by temperature. At finite temperature and rotational frequency the nucleus can be viewed as an ensemble of shapes with a distribution controlled by the Boltzman factor [9,10]. An averaging of the GDR vibrations over the distribution of shapes is therefore necessary to predict the GDR width.

There is a very large systematic of experimental data up to 2 MeV of nuclear temperature, most of the data have been successfully interpreted by the thermal fluctuation model. Unfortunately, in the case of higher temperature (T > 2.5 MeV) there are few experimental available data and they are mainly concentrated in the mass region between A=110 and, as a results of the previous HECTOR-GARFIELD campaign, A=130 [11]

In the first experimental HECTOR-GARFIELD campaign it has been measured the gamma decay of the GDR in very hot ^{132}Ce*. Five different reactions producing ^{132}Ce at the kinematical value of excitation energy E^* = 100, 150 and 200 MeV has been performed. Symmetric (using ^{64}Ni as a projectile) and asymmetric (using ^{16}O as a projectile) reaction channel have been used. The goal of the first experimental campaign was the study of the damping mechanisms of the collective dipole vibration which are at work at high temperature (T>2 MeV) and the cooling mechanism which is active in such a temperature region.

The picture deduced from our measurements shows that the GDR width does not saturate at T > 2.5 MeV as previously observed but increases steadily with temperature at least up to 4 MeV (see figure 1) [11]. Deformation effects and intrinsic lifetime of the compound nucleus have been identified as the two combined mechanisms which explain the measured increase of the width with temperature.

In addition, the measured light charged particles spectra have shown that the compound nucleus produced with the Ni induced reactions, namely using the symmetric reaction, is fully thermalized while statistical model calculations cannot describe the large extra yield measured in the O-induced reactions for which incomplete fusion mechanisms are open.

The experimental results of the HECTOR-GARFIELD first campaign confirms what suggested in ref [12] and have significatively changed the scenario of the collective dipole motion in very hot nuclei. Besides, our data has shown that the initial excitation energy of the decaying nuclei has to be experimentally measured using light charged particles in coincidence with GDR high energy gamma rays. In fact, pre-equilibrium emission might play an important role in the cooling of the nucleus before a fully thermalized compound nucleus is formed. We have experimentally observed that only in very symmetric fusion-evaporation reactions the compound nucleus has the nominal kinematical value of the excitation energy. In the case of asymmetric reactions up to 20-30% of the excitation energy is dissipated before the compound nucleus is fully thermalized.

As the great majority of the available GDR data at high temperature (T>2 MeV) has been performed using asymmetric reactions [13-15], in most of the cases this might have induced an overestimation of the compound nuclear temperature [12]. It is consequently important to envision measurements of the GDR properties at high temperature in a mass region different from A=130 using symmetric reaction where high energy gamma rays, light charged particle and evaporation residues could be measured in coincidence.

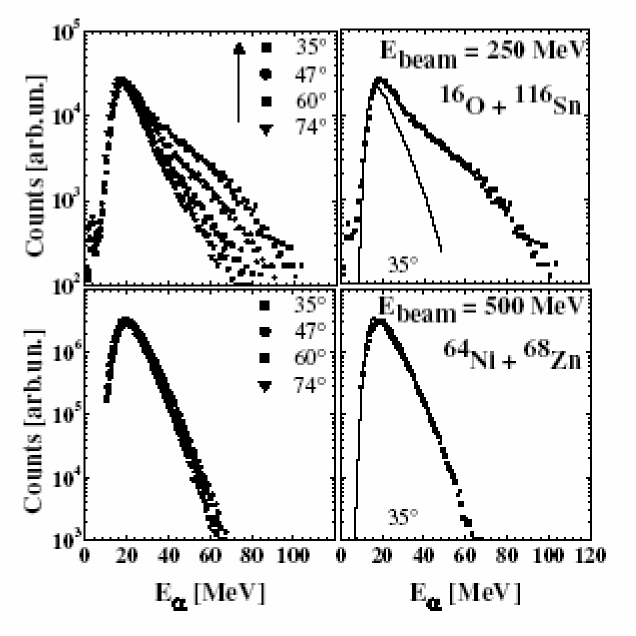

Figure 1 *Comparison between measured (black points) and calculated GDR width at <J> = 45 .*
The thick continuous line shows the calculations where also the change in the compound nucleus (CN) lifetime is included in the thermal shape fluctuation simulation. The thin continuous line indicates the results where such effect is not included. The dashed line shows the average deformation $<\beta>$ calculated by the thermal fluctuation model (scale on the right axis)[11].

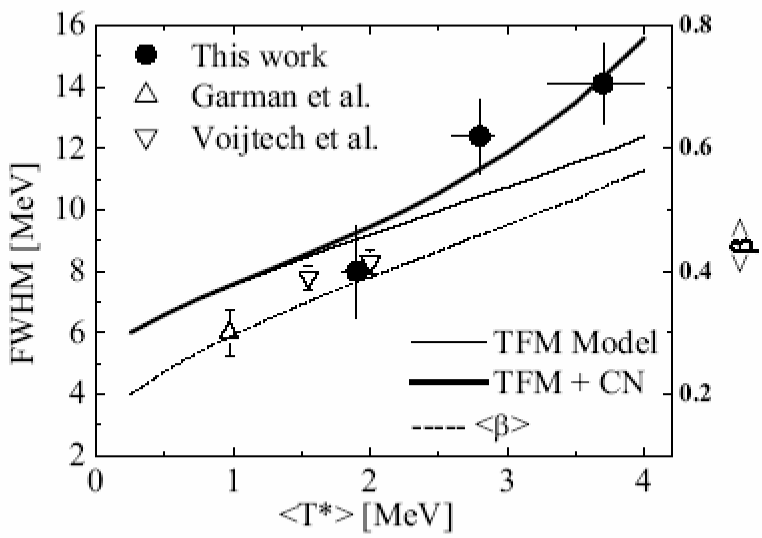

Figure 2 *Left panels: measured alpha-particle spectra in the CM frame system at different detection angles for the two different mass entrance channel reactions. The lower panel shows the measured yield for the Nickel-induced reaction (E_{lab}=500 MeV). The upper panel shows measured alpha-particle spectra for the Oxygen-induced reaction (E_{lab}=250 MeV).*
Right panels: measured alpha-particle spectra at 35^o in the CM system for the Oxygen and Nickel induced reactions. The continuous line in both right panels indicates the results of statistical model calculations [11].

In this new HECTOR-GARFIELD campaign we intend to submit a proposal on the measurement of the GDR properties in the A = 80 mass region where the fusion-fission channel is rather weak, particle emission is strong and the GDR quenching effect is not expected to play an important role as it should start at temperature higher than 5 MeV. At least three points at increasing temperature 3, 4 and 5 MeV will be requested.

A possible reaction uses pulsed ALPI-TANDEM ^{48}Ti beam on a ^{40}Ca target. Possible beam energies are 180, 320 and 550 MeV. An estimated beam time of 30 shift (approximately 9 shift for each beam energy plus 3 shift for setup and calibration using the ^{11}B (45 MeV) on D target for BaF_2 calibration. A more detailed study of the reaction and of the required beam time and energy will be done as the proposal will be submitted.

A possible extension of this part of the program is in the A=200 mass region. In this case, as the fusion-fission channel will be strong we intend to study the GDR properties at lower temperatures namely 2,3 and 4 MeV. We are still working for the identification of the optimal projectile-target combination.

3) Search for the Jacobi shape transition in light nuclei

It is known that a nucleus changes its equilibrium shape from spherical (or prolate) to oblate under the stress of the centrifugal force. In hot nuclei the size of the oblate deformation increases with the angular momentum and, at certain critical value of spin, an abrupt change of the equilibrium shape from an oblate non-collectively rotating ellipsoid to a triaxial or prolate rotating body, is expected, with the nucleus evolving to more and more elongated shapes. This phenomenon, called nuclear *Jacobi transition* was theoretically studied in the past using, among others, semi-classical models (see e.g. [16] and references therein). Recently the newly developed model [17] called LSD (Lublin-Strasbourg Drop) gives more realistic predictions which nuclei and spin windows may permit the observation of the expected the Jacobi transition. Alternately, theoretical calculations that include thermal shape fluctuations in nuclei have been used recently to understand the Jacobi transitions [18,19].

The effects of large deformations due to the Jacobi transition are of particular interest in the case of light mass nuclei. First of all, this is the best case to clearly observe the very elongated shapes, since the critical angular momentum for Jacobi transitions is well below the critical angular momentum for fission, and therefore the spin window for the triaxial or prolate elongated shapes is larger. This can be seen in Fig. 3, where the evolution of equilibrium shape of ^{46}Ti calculated within the LSD model is shown as a function of angular momentum. The Jacobi transition appears at 28$\hbar$, whereas the angular momentum at which the fission barrier vanishes at 38$\hbar$ [20] was found in Refs. [21,22]. In fact, in this nucleus the very elongated triaxial shapes have been observed in the spectra of the giant dipole resonance (GDR) in a VIVITRON experiment done with the EUROBALL and HECTOR arrays [23] (see Fig. 4), and in addition strong deformation effects on α-spectra were indicated in an ICARE experiment [24].

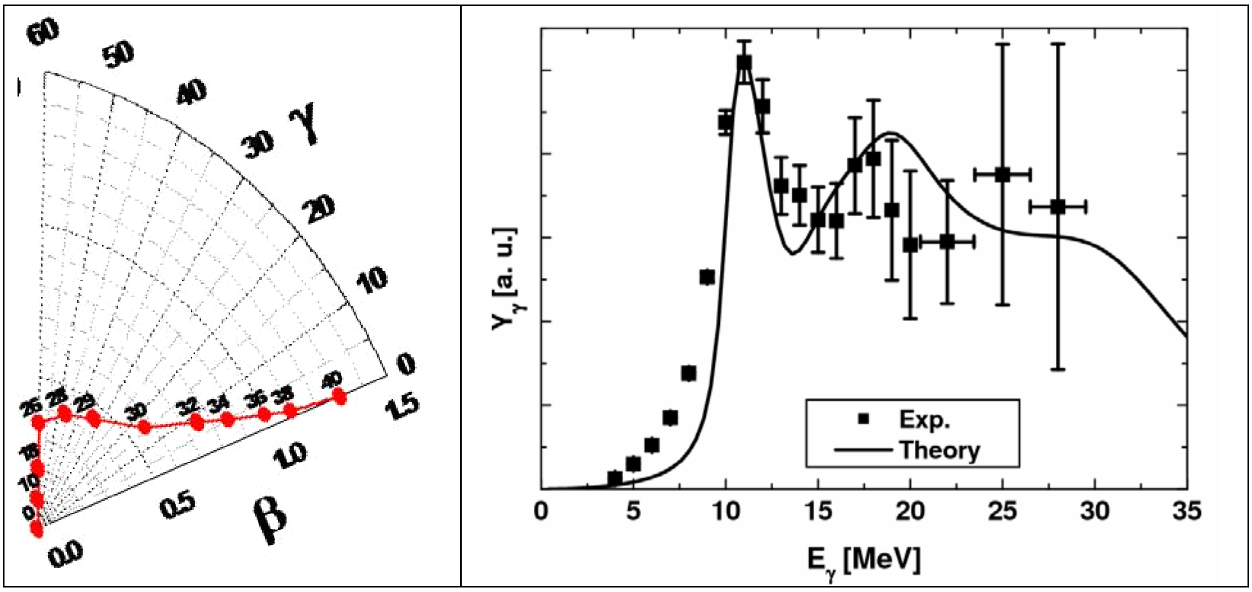

Figure 1 *Left: LSD model prediction of the shape evolution of ^{46}Ti as a function of angular momentum. Right: The experimental GDR strength function for ^{46}Ti at high spins compared to predictions based on the LSD model for the Jacobi shape regime.*

Secondly, the existence of highly- and super-deformed bands in a number of light mass nuclei was found [25-27]. It was shown in [28], that there might be a correlation between the Jacobi shape transitions in the hot compound nucleus and the feeding of the superdeformed bands. And finally, a number of molecular resonances, associated with extreme deformations have been also observed in light nuclei: the most spectacular results have been obtained for ^{48}Cr (in ^{24}Mg+^{24}Mg collision) and ^{56}Ni (in ^{28}Si+^{28}Si) [29].

In light nuclei the evaporation process evolves mainly via light charged particle (LCP) emission [20,21]. As the energy spectra and the angular distributions are sensitive to the nuclear deformation both of the parent and daughter nuclei through the evaporation cascade, a study of the particle evaporation constitutes a good tool for investigating the onset of very elongated shapes. However, for the unique determination of the existence of the predicted Jacobi shapes in hot compound nuclei, and deformation of consecutive evaporation residues, one needs a *simultaneous* measurement of the γ-decay of the GDR and charged particle spectra at different angles. The use of the coupled GARFIELD array with HECTOR array was proven in earlier experiments [11] to be a very efficient tool to achieve such a goal.

The aim of the proposed experimental program is to measure the GDR γ-decay as well as the energy spectra and angular distributions of the LCP emitted by the hot nucleus from the high angular momentum region and compare them to the spectra emitted from the low angular momentum region of slightly deformed oblate shapes. This will be achieved by performing an experiment at 2 bombarding energies and selecting the charged-particle decay from the highest angular momenta by gating on the residues with the highest Z. Also different beam-target combinations are planned to be used in order to take into account the possible entrance channel effects

We plan to perform a series of experiments to investigate the α-like nuclei: ^{32}S, ^{36}Ar, ^{40}Ca, ^{44}Ti, ^{48}Cr and ^{56}Ni. A possible first experiment will be concentrated on ^{44}Ti, studied extensively by the Strasbourg group [30] using the ICARE charged particle array [21,22,24], in which signatures for a strong deformations were found in the spectra of emitted α-particles. For this particular experiment we plan to use 2 reactions: ^{16}O (112 and 70 MeV) + ^{28}Si and ^{32}S (260 and 170 MeV) + ^{12}C, leading to the compound nucleus ^{44}Ti with E*=83 and 56 MeV and l_{max}=34 and 27$\hbar$, respectively.

4) Onset of the multifragmentation and the Giant Dipole Resonance

The study of nuclei under extreme conditions is a major issue of nuclear physics. For example the highest excitation energy a nucleus can sustain has driven a large number of investigations. Among these works, it is worth noticing that properties of excited nuclei have been widely studied by means of two independent probes: the temperature dependence of collective modes as Giant Dipole Resonance; the fate of the compound nucleus picture and the onset of the Multifragmentation process, i.e. the simultaneous breaking of nuclear system into several pieces of intermediate masses.

It was proposed that hot GDR is a good indicator of the cohesion of excited system. Conversely the disappearance of the GDR might be considered as a signature of a transition towards a chaotic regime [31]. 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 the collective motion is around 5 A MeV for compound nuclei of masse 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 system. Multifragmentation, is a very common disintegration mechanism for hot nuclei produced in heavy-ion induced reactions. Its threshold has been evaluated to excitation energy values of 2-3 A MeV (temperature close to 5 MeV) by numerous studies performed in large collaborations using powerful 4π LCP arrays such as DELF, AMPHORA, MiniBall, ISIS, ALADIN, EOS, INDRA. For example a systematic on caloric curves allows extracting the temperature (or conversely the excitation energy) at which the caloric curve starts to deviate from the standard Fermi gas behavior and develops a "plateau" or a "kick". These limiting temperature are of the same order of magnitude of those deduced from GDR studies.

Thus by combining both set of data it seems that the lost of collective motion and the gradual disappearance of the GDR could be linked to the appearance of new fragmentation mode such as multifragmentation [31]. It is worth noticing that up to now, no attempt has been made to establish a firm correspondence between both signatures. The issue of the present part of the proposal is to elucidate whether such a link is at work.

It should be mentioned that the limiting temperature deduced from the caloric curve have been determined for a wide range of masses while data on the limiting temperature of the collective motion and hot GDR covers a restricted range and nothing is really established above A=120 on the lost of collective motion. This lack of data for heavy nuclei is worth noticing since finite size and coulomb effects play a definite role in both collective modes and instabilities.

What is proposed here is to measure simultaneously high-energy γ-rays and charged products. This will require coupling very efficient high-energy gamma rays detector with a powerful charged products array. This has been done recently at the LNL facility for a couple of reactions Ni+Zn around 8 A MeV using both HECTOR and GARFIELD arrays together with an ensemble of PPAC to detect the residues [11].

We plan to perform a series of experiments using both LNL Legnaro beams (with GARFIELD + HECTOR setup) and GANIL beams (with INDRA + HECTOR setup). We plan mainly to explore three mass regions: A=120 (typically Ni + Zn), A=160 (typically Mo+Mo, Se+Ge) and A=200 (for example Xe+Sn). In order to explore possible dynamical effects we want to measure both compound nucleus and deep inelastic collisions [32]. The studied systems can be extended to the one delivered by the future SPIRAL2 facility, when also the isospin effects on the onset of multifragmentation can be studied.

The possible first experiment that can be performed at LNL Legnaro using the GARFIELD and HECTOR array can be the same system as in Ref. [11], namely ^{64}Ni + ^{68}Zn, but a higher bombarding energy of 700 MeV. This reaction leads to the formation of the compound system, ^{132}Ce, at 300 MeV excitation energy at which the onset of multifragmentation is expected.

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