# Title: Direct Reaction Studies of Exotic Nuclear Structure


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***Abstract:***

The GASPARD collaboration, formed after the SPIRAL2 Workshop on Reactions, held at GANIL in October 2005, proposes the construction of a next-generation detection array for direct reaction studies at SPIRAL2.

The present letter of intent outlines the compelling physics case that will be addressed by the GASPARD array and describes its conceptual design. Themes central to nuclear physics such as the evolution of shell structure, modification of the spin-orbit interaction, changes to nucleon-nucleon pairing in the isospin asymmetric medium, clustering, reaction mechanisms and aspects of nuclear astrophysics will be explored. GASPARD is designed to overcome the new experimental challenges that the beams from SPIRAL2 will present. The array will provide fully integrated 4π particle and 4π gamma detection with efficiency and solid angle coverage that is greatly improved over present-day devices such as MUST2 and TIARA.

## **Scientific case** (Typically 2-3 pages)

### Introduction

Direct reactions are a unique tool for the investigation of nuclear structure. The relative simplicity of the reaction mechanism, involving only a few degrees of freedom, allows precise theoretical calculations to be made and nuclear structure information to be extracted from experimental data. Hence, direct reactions have been used extensively in the past with stable beams and have contributed greatly to our present knowledge of stable nuclei. Recently, with the advent of radioactive ion beams, it has become possible to use direct reactions to study exotic nuclei. Such studies are revealing the dramatic changes that occur both in the nuclear structure and in the reaction mechanism itself. SPIRAL2 is truly a next generation facility that will allow a greatly increased range of exotic nuclear systems to be produced and studied. Direct reactions will constitute one of the most important experimental tools to be used at SPIRAL2.

At GANIL, the instrumentation and methodologies have been developed in the last 10 years to study these reactions in inverse kinematics, which is necessary when using RIBs. A notable example is the MUST detector array, which has been extensively used to study elastic, inelastic and transfer reactions. More recently, the TIARA array has been developed specifically to allow the simultaneous detection of both particles and gamma rays. The most recent device, MUST2, will offer new capabilities for the detection of multi-particle events. In the short term, the TIARA and MUST2 arrays will be combined by the respective collaborations to create a powerful setup for the study of direct reactions with both the SPIRAL (ISOL) and SISSI (fragmentation) beams available at GANIL.

**While this current generation of instrumentation is giving successful measurements, it has become clear that significant improvements need to be made in efficiency, resolution and simultaneous particle and gamma detection to fully exploit direct reaction studies with the SPIRAL2 beams.** Following the SPIRAL2 Workshop on Reactions, held at GANIL in October 2005, an international Working Group (WG) has been formed to formulate a conceptual design for such a next-generation device, named **GASPARD**.

The purpose of this Letter of Intent is twofold:

(i) to highlight several physics areas that will be studied using direct reactions at SPIRAL2:
- single-particle structure
- nuclear pairing
- spectroscopy of very neutron-rich nuclei
- nuclear clustering and nuclear molecules
- direct reaction mechanisms
- applications to astrophysics

(ii) to present a first conceptual design of the new detector system, GASPARD.

**Single-Particle Structure**

Far from stability, a dramatic evolution of nuclear shell structure is expected, as the result of a delicate interplay between several physical effects; for example, mean-field changes (e.g. spin-orbit interaction), proton-neutron (tensor) interaction, pairing, coupling to the increasingly close continuum, etc. The resulting migration of single-particle levels leads to different observable consequences, e.g. reduction of the splitting between spin-orbit partners, vanishing of magic gaps, etc. Investigations of these have already started at GANIL/SPIRAL for light and medium-light nuclei, in particular near the N=20 and N=28 magic numbers. SPIRAL2 will allow this shell evolution to be systematically investigated using high quality beams of a wide range of medium-mass nuclei.

The energy regime of SPIRAL2 is well-suited to transfer reactions. One-nucleon transfer reactions such as (d,p), (p,d), (d,$^3$He), (d,t) etc. are well known to give access to single-particle properties of nuclei and the underlying shell-structure. Energies, quantum numbers of the states and spectroscopic factors can be reliably extracted, in particular when using beam energies between the Coulomb barrier and a few tens of A.MeV. Among recent achievements obtained using such reactions at GANIL, we mention :

- demonstration of the shell inversion between $2s_{1/2}$-$1p_{1/2}$ in the ground-state of $^9$He by using the $^8$He(d,p)$^9$He reaction,
- reduction of the gap between the spin-orbit partners in $^{47}$Ar observed in the $^{46}$Ar(d,p)$^{47}$Ar measurement,
- raising of the $d_{3/2}$ neutron orbital and the opening of the N=16 shell closure across the N=15 isotones using the $^{24}$Ne(d,p)$^{25}$Ne reaction.

With SPIRAL2, intense beams in the N=82, $^{132}$Sn region will be available. One can envisage to study the eventual migration of the $h_{11/2}$ orbit which may reduce the N=82 gap and enhance the gap at N=70.

As an alternative to transfer reactions, resonant elastic scattering can be used, at least for the proton shells, to extract essentially the same information.

**Nuclear Pairing**

The evolution of pairing effects with isospin and with nuclear density is an important question. For example, it is predicted that the pairing gap increases with neutron excess, an effect that is related to the density dependence of the pairing interaction and the lower density associated with skins and haloes. In a low-density neutron skin formation of di-neutron clusters is also predicted [1].

The development of SPIRAL2 will allow many very neutron-rich nuclei to be produced for the first time. By studying the pairing correlation in neutron-rich nuclei, it will be possible to distinguish between various interactions deduced microscopically from different effective nucleon-nucleon forces. This will elucidate the microscopic origin of the pairing interaction and the role of finite range and density dependence. SPIRAL2 will also allow the pairing between neutrons and protons to be systematically explored. n-p pairing can occur in both the T=1 and T=0 channels and, while T=1 n-p pairing should be similar to n-n and p-p pairing due to charge independence, the characteristics of T=0 (deuteron-like) pairing are largely unknown. Such an interaction should be particularly strong in N=Z nuclei where the wave function overlap between neutrons and protons is important. Proton-rich N=Z nuclei will be produced at SPIRAL2 with much larger intensities than have previously been available and will allow this form of pairing to be systematically explored.

An experimental observable to probe the strength of the pairing correlations is the probability of reactions in which a pair of nucleons is transferred between projectile and target. Two-nucleon transfer reactions, for example the (t,p) or (p,t) reactions in the case of n-n pairs, would be performed in inverse kinematics. The ($\alpha$,$^{6}$He) reaction may be a tool for the transfer of a di-neutron cluster. In the case of n-p pairing, (p,$^{3}$He) or (d,$\alpha$) reactions can be used in order to investigate the competition between T=1 and T=0 pairing.

**Spectroscopy of Very Neutron-Rich Nuclei**

Another application of two-nucleon transfer is to reach very neutron-rich nuclei, even beyond the neutron drip line. Starting from an already neutron-rich beam, one can either add 2 neutrons or remove 2 protons by using respectively the (t,p) or the ($\alpha$,$^{6}$Be) reactions. Using these reactions, the low-lying excited states can be populated and identified through their angular distributions. Triton targets can be obtained in the form of Ti loaded material (commercially available), and alpha targets can be in the form of gaseous cryogenic targets. Concerning light ion beams produced by SPIRAL2, we mention that the six-neutron system will be directly reachable using the ($\alpha$,$^{6}$Be) reaction induced by the intense (few $10^{8}$ pps) $^{8}$He beam expected.

**Nuclear Clustering and Nuclear Molecules**

The occurrence of nuclear molecules is presently rather well understood in reactions induced by alpha-like nuclei ($^{12}C+^{12}C$, $^{16}O+^{16}O$, $^{24}Mg+^{24}Mg$, and $^{28}Si+^{28}Si$) in terms of alpha-clustering. Experimental signatures of the Bose-Einstein condensation of alpha clusters in the atomic nucleus have also been reported. Isospin asymmetric nuclei are also expected to display exotic spectroscopic features such as molecular states and clusterings [2,3]. Such exotic cluster states in light nuclei close to the proton dripline have been investigated recently by using $^{6}He$ radioactive beams at GANIL and Louvain-la-Neuve. Reactions induced by $^{6}He$, a nucleus with a Borromean structure with two weakly-bound neutrons and an alpha-particle core, is well suited to such studies. Adding more particles to this loose extended object will produce nuclei in states that resemble a molecular configuration in a manner extremely similar to the exchange of electrons in covalently bound atomic molecules. The existence of molecule-like structures has still to be demonstrated in heavier non- alpha-like di-nuclear systems. From molecular models, such as the one based upon Antisymmetrized Molecular Dynamics (AMD), for instance, it is anticipated that very neutron-rich C or Ne isotopes as projectiles (with high intensities as provided by SPIRAL2) might be the best suited for the search of very exotic molecular configurations (like the "nuclear water" predicted by the extension of the well-known Ikeda diagram [2]). It is already clear that the $^{14}C+^{14}C$ reaction shows pronounced molecular resonances in direct reaction exit-channels. Studies of the process by which the cloud of valence neutrons is exchanged between the cluster cores with beams of $^{6,8}He$, $^{15,16,19}C$, $^{11}Be$ and $^{23,25}Ne$ nuclei should provide an insight into the possible structures at the drip-line.

The high angular and energy resolution characterizing the GASPARD array will allow using two- or multi-particle correlation measurements with all particles produced in the breakup of these exotic unbound states. Their spectroscopic properties, such as the energy and the spin can be explored experimentally [3-5]. Furthermore, multi-particle correlations will provide unique tools to disentangle different decay modes and access information about the competition between simultaneous breakup processes and sequential emission through intermediate unbound states [6,7]. These studies can be extended to both the proton-rich and the neutron-rich sides of the nuclear chart. Multi-particle correlations can therefore require the simultaneous detection of both charged and uncharged radiations. Such requirements can be achieved by GASPARD and by coupling the device to neutron detectors.

**Direct Reaction Mechanisms**

Direct reactions are such a useful tool to study nuclear structure because the reaction mechanism involves only a few degrees of freedom. This relative simplicity allows precise theoretical calculations to be made using, for example, the Distorted Wave Born Approximation (DWBA). Indeed the validity of such an approach was demonstrated extensively in the past with studies of stable nuclei. However, it has recently become apparent from studies of direct reactions with exotic nuclei and weakly-bound stable nuclei that such a simplified approach to the reaction mechanism is no longer sufficient and that effects such as coupled channels, proximity of the continuum and core excitation become important. This has led to the introduction of more sophisticated theoretical techniques such as Continuum Discretized Coupled Channels (CDCC) and its recent extension XCDCC.

To progress in this direction, studies of the direct reaction mechanism using exotic nuclei need to be made and confronted with these more comprehensive theoretical approaches. Such studies are extremely interesting from the point of view of understanding the direct reaction mechanism itself, but they are also vital if precise nuclear structure information is to be extracted from them. They will also provide unique information on the dynamics of three- and four- body quantum systems, which are poorly understood at present.

Near-barrier reactions with halo and cluster nuclei such as $^{6,8}$He, $^{11}$Be, $^{11}$Li, $^{15,19}$C and $^{17}$Ne, which are weakly-bound and have well-defined breakup and fusion modes, are good testing grounds for these theoretical approaches and such nuclei will be available with high intensities at SPIRAL2. Reactions with both light- and heavy-ion targets will need to be studied to examine the effects of different channel couplings. The proposed GASPARD array is well suited to making high precision measurements of the elastic, inelastic, transfer, break-up and fusion angular distributions and partial cross-sections of these light exotic nuclei.

**Applications to Astrophysics**

The future SPIRAL2 facility will contribute prominently to several areas of active research in nuclear astrophysics, such as explosive hydrogen burning, s-process and r-process nucleosynthesis, which are linked to astrophysical observations such as novae, X-ray bursts, AGB stars and type II supernovae. These stellar processes involve networks of nuclear reactions (with charged particles or neutrons) and $\beta$-decays. To determine nuclear reaction rates, indirect methods have been developed to circumvent the experimental difficulties due to either the vanishingly small cross-sections at astrophysical energies of reactions involving charged particles, or to the radioactive nature of the nuclei in the entrance channel. For example, radiative capture cross-sections can be determined from spectroscopic factors (or Asymptotic Normalization Coefficients) obtained in transfer reaction or elastic resonant scattering. From a general point of view, detailed spectroscopy of the nuclei of interest is crucial to ensure efficient application of indirect methods, which can be obtained by using these two reactions.

For an illustration of future work, the (d,p) reaction can be used to simulate the (n,$\gamma$) capture on medium-mass nuclei at SPIRAL2 near the r-process possible paths [8]. The measurement of the (d,p$\gamma$) reaction is also to be considered since it gives access to the $\gamma$-widths of the exit channel. Such studies are closely related to the investigation of low energy dipole strength. The presence of such pygmy states near the neutron emission threshold can enhance capture rates by very large factors.

Finally, we mention that the investigation of nuclear pairing in neutron-rich systems is also of fundamental importance to describe the superfluidity at work in the crust of neutron stars. It has been shown recently that the cooling time of such stars is very sensitive to pairing effects and it is therefore of major importance to better constrain the pairing interaction in neutron-rich low-density nuclear matter. Direct reactions aimed at probing pairing in diffuse neutron-rich systems could validate the theoretical approaches to neutron matter. This issue will be tackled using neutron-pair transfer reactions, as mentioned above.

## **Methodology** (Typically 2-3 pages)

We propose the development of a new, fully integrated, 4π particle and 4π gamma array for the study of direct reactions: **GASPARD** (**GA**mma **S**pectroscopy and **PAR**ticle Detection). This array will be optimized to exploit the scientific opportunities that will be offered by the new SPIRAL2 facility outlined in the previous section.

Major new challenges will be imposed on the detection systems by the beams from SPIRAL2, challenges that present-day systems such as MUST2 and TIARA will be unable to meet. For example, a large part of the beams species delivered by SPIRAL2 will be fission fragments. It is well known that such medium-mass nuclei have increased level densities in comparison to the low-mass nuclei available today from the SISSI/SPIRAL beams at GANIL. A system with experimental energy resolution that is dramatically improved over present-day arrays therefore needs to be developed. Additionally, the structure of exotic nuclei will be strongly influenced by the proximity of continuum states and thus the properties of both bound and unbound excited states will be important to study. The detection system must therefore be able to identify and measure both types of states. Further, recent direct reaction studies with exotic nuclei have shown that it is very important to include the coupling of different reaction channels to reach a comprehensive description of the reaction mechanisms involved. It is likely that such effects will become increasingly important in reactions involving the more exotic nuclei produced by SPIRAL2. The detection system must therefore be able to measure simultaneously as many reaction channels as possible.

The aim of the GASPARD collaboration is to design an array that will overcome these new experimental challenges. The basic concept of the array is to provide the simultaneous detection of recoil particles and γ-rays in a fully integrated and seamless way, with the maximum possible efficiency and solid-angle coverage. Such techniques will gain a large factor in excitation energy resolution compared to particle detection alone and permit the use of thicker targets to increase the available luminosity. The reaction channel selection and the spectroscopic information obtained will also be greatly improved. All essential reaction channels will be measured simultaneously, together with scattering to both bound and unbound excited states.

In the present MUST2/TIARA devices, the efficiency for the coincident detection of gamma-rays and particles is low since there is insufficient geometrical overlap between the two detectors. GASPARD will offer solid angle coverage close to 4π for both particles and gamma-rays. In such a "4π"+"4π" ensemble, the gamma detectors will surround the particle detectors and also be used to detect the fast charged particles. The granularity of the gamma detector will be determined by the requirement of balanced contributions between intrinsic and Doppler-induced resolution. The system will be designed such that it will function with both SPIRAL2 and fragmentation beams. Overall, the array should have particle identification (PID) with excellent position and angular resolution (~0.1-0.5 mm and 1-5 mrad, respectively), together with large dynamic range and PID capabilities to at least Z = 10. The gamma detection stage must have the best possible efficiency, surpassing that typically achievable with Ge for example. GASPARD will also be designed to couple to ancillary detection systems. For example, the magnetic spectrometers VAMOS and SPEG will be necessary for detection of the projectile-like fragments. Additional equipment, such as beam tracking detectors as well as cryogenic targets are also in preparation.

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

All the beam species that SPIRAL2 will be able to produce are potentially of interest for our direct reaction experiments. Minimum rates required are ranging from a few hundred pps to a few $10^4$ pps. In many cases, however, SPIRAL2 can produce nuclei of interest with beam intensities greater than $10^6$ pps and we wish to use these. However, at such rates beam tracking is impossible. In order to make the measurements without beam tracking detectors, the beam quality must be high. For example, the beam emittance must be low in order to give sufficient angular resolution that, in turn, affects the resolution of the reconstructed excitation energy. **Ideally the beam spot size should be no larger than 1mm FWHM. Additionally, the RF signal should have a resolution of better than 1 ns**, to allow the identification of recoil particles in the energy domain where the E-TOF technique is used. In other recoil energy domains, pulse shape discrimination will be used.

At lower rates, below $10^6$ pps, beam tracking is possible and the further development of Beam Tracking Detectors (BTDs) will be undertaken within the collaboration. These will give the position on target with a resolution of 0.5 mm and an angular resolution of 0.2°. The device should have a time resolution below 0.5 ns for ions heavier than Ne. What is crucial with the BTD for SPIRAL2 beams is to have a small amount of material intercepting the beam. The SPIRAL2 beams will be medium-mass ions with high charge and relatively low energy thus the thickness of the material intercepting the beam has to be below 50µg/cm$^2$ of equivalent carbon foils. R&D programs are underway on these devices.

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

For reaction studies using the recoil particle technique, relevant target thicknesses are typically 1 mg/cm$^2$. Apart from standard $CH_2$/$CD_2$ solid targets, the GASPARD collaboration plans to use cryogenic targets (solid or gas) which are presently being employed and developments in progress. A typical application would be the ($^3$He,d) proton stripping reaction, to which the only alternative reaction is (d,n). This reaction is of high interest to study the proton shells as well as for astrophysical applications.

Polarized targets will also be studied. Asymmetry measurements with a polarized p, d, or $^3$He target give access to spin observables (analyzing powers). For a one nucleon transfer reaction, this gives an unambiguous determination of the spin and parity of the final state. The integration of such a target into GASPARD is challenging. The use of other targets like triton targets under the form of Ti loaded material (commercially available) can be envisaged. It would allow us to perform reactions such as (t,p), giving a powerful spectroscopy tool for very neutron-rich nuclei.

Heavier stable targets such as C, Ni and Pb will also be needed in particular to study the reaction mechanisms involved. For example, $^{208}$Pb targets can be chosen to provide large Coulomb fields. Other targets can be chosen according to the properties of the reaction mechanism under study.

***Instrumentation and detectors*** *(equipment to be constructed or modified):*

The proposed GASPARD array is made up of two components: the **Particle Array (PA)** and the **Gamma Array (GA)**. The PA will cover a solid-angle of 4π with highly-segmented telescopes of position-sensitive semiconductor and scintillator detection layers (ΔE+ΔE+E) surrounding the reaction target. The GA will consist of a highly-segmented array of scintillation crystals arranged in a spherical geometry and also covering 4π solid-angle. It will be fully integrated mechanically with the PA and will be placed in vacuum. R&D into the crystal material will be needed but possibilities include CsI, $LaCl_2$ or $LaBr_3$(Ce). To allow low-energy particle discrimination thresholds, a time of flight technique will be employed for energies below approx. 8 A.MeV (punch-through of the first ΔE layer). The start signal will be derived from the HF and/or the beam tracking. Above this value, energy loss methods will be used (ΔE+ΔE+E).

Modularity of the mechanics, front-end electronics and data acquisition is an essential feature of GASPARD. It gives flexibility to the array and increases its physics scope by allowing the possibility of introducing other detector types, such as neutron detectors, FAZIA modules and EXOGAM/AGATA modules.

In brief, the instrumentation to be developed will have the following specifications:

**Particle Array (PA):**

- Position resolution of 0.5 mm over ~4π for direct reaction studies and 0.1 mm for particle correlation studies in the forward direction.
- Dynamic range sufficient to cover from fast proton measurements (50 keV in the first thin DSSD) up to quasi-projectile 1000 MeV energy losses. The low threshold will allow high-energy protons to be detected in thin ΔE detectors.
- Combined time-of-flight measurement and pulse shape discrimination will allow low energy particle identification.
- Low mass budget to achieve a gamma-ray absorption in the PA of below 10% for 1 MeV gammas. This principally refers to detector frames and a modular system such that a minimum of material is introduced in the GA.

**Gamma Array (GA):**

- 50 keV (FWHM) energy resolution for gammas of 1 MeV
- Dynamic range from 0.1 to 5 MeV. Will also need to stop high energy charged particles. Full dynamic range to be determined
- Total detection efficiency of 75% for 1 MeV gammas.
- Granularity will be such that the Doppler broadening is below 30 keV.

The number of channels needed is ~13 000 for the PA and ~2 000 for the GA. These estimates are based on a spherical geometry with 40 cm inner diameter, covered with DSSD based telescopes and backed by scintillator crystals.

**Electronics specifications:**

- A switchable dynamic range/and pre-amps to cover different detector types and dynamic ranges

   - 0.05 to 10 MeV (50µm Si DSSD)
   - 0.15 to 50 MeV (300µm Si DSSD and CsI equivalent)
   - to 1,000 MeV (quasi projectile measurements)
- Electronic energy resolution of 15 keV (FWHM) for the dynamic range 0.15 to 50 MeV in particular.
- Time range switchable from 500nsec to 5µsec. Time resolution of 200 psec (FWHM) for the 500nsec range in particular.
- PSD–sampling at 2 GHz with 14 bit.
- The coupling with VAMOS, SPEG and modules of FAZIA, EXOGAM, AGATA and neutron detectors will be taken into account for the hardware and software design.
- 10 kHz counting rate with 10% dead-time.

It is to be emphasized that several technical concepts can be used to reach the above requirements. However, the baseline solution presented here comes largely from our experience with present-day arrays such as MUST2 and TIARA. The PA will use large area Si-based solutions with ΔE-ΔE-ΔE telescopes (max total thickness of 5 mm of Si) giving measurements of the pulse shape, energy and time. The major differences with respect to the present generation of front end electronics are the following:

1. Requirement to have low gamma-ray absorption. Envisaged solution is to separate the pre-amplifier stage from the main front-end. This has the advantage that it will allow different types of detectors (high granularity of strips, Si(Li) detectors, CdTl, diamond, photomultiplier or avalanche photodiodes etc) to be treated at the expense of a multi-choice switchable pre-amplifier chip. This design has the additional advantage that it leaves open the possibility of utilizing new detection material/detectors that will come on the market in the future.
2. PSD: sampling of a current signal for charge and mass identification.
3. Improved energy resolution: a multi-stage amplifier.
4. Selective read-out to allow a small number of channels to be read out of 15,000.
5. Fast Read-out: Time stamping along with selective read-out to allow a large throughput of events.

These specifications are sufficiently different from those available today to require extensive R&D into the detector materials, characteristics and the micro-electronics.

**These developments will be undertaken by the GASPARD collaboration over the next 3 years. It is important to note that to date only rough calculations have been done to back up this document and that full simulations will need to be carried out during the R&D period.**

A preliminary task sharing, taking into account the capabilities of each institution, are detailed in the following table:

| **Task** | **Institute** |
|---|---|
| Tests and simulations of charged particle detector responses, pulse shape discrimination | CEA-Saclay, IPN-Orsay, GSI, Surrey University, Paisley University, Huelva University |
| Tests and simulations of different scintillator crystals, gamma ray detector responses | Santiago de Compostela University, IPN-Orsay, ATOMKI Debrecen |
| ASIC design | CEA-Saclay, Huelva University, CCLRC Daresbury Laboratory |
| Front-End Board design | CCLRC Daresbury Laboratory, Huelva University |
| Mechanical design of GASPARD and integration of PA and GA | Liverpool University, CCLRC Daresbury Laboratory, IPN-Orsay |
| Data Acquisition | GANIL, KVI, IPN-Orsay, CCLRC Daresbury Laboratory |
| Control Command | KVI |

***<u>Theoretical support</u>*** *(short description of the necessary calculations and developments):*

Traditionally, direct reactions have been modelled using Distorted Wave Born Approximation (DWBA) techniques. Such an approach can be successfully applied to reactions involving stable nuclei. However, DWBA techniques are less suitable when applied to reactions involving exotic nuclei. For such reactions, effects such as coupled channels, proximity of the continuum and core excitation become important. To describe pair transfer, microscopic form-factors have to be calculated using e.g. state-of-the-art mean field theory. For example, form-factors including n-p pairing effects have to be calculated. It is therefore important to use more sophisticated techniques to model such reactions. Tools such as Continuum Discretized Coupled Channels (CDCC) and its recent extension XCDCC are currently under development worldwide and will be of vital importance in analysing the new data from direct reaction studies at SPIRAL2. Techniques to describe and discretize the three- and many-body continuum will also be of great importance. A proper understanding of the three-body dynamics, introducing concepts such as transfer to the continuum, is required. The collaboration is working with theory groups at institutions such as the University of Surrey (UK), IPN-Orsay (France), CEA-Saclay (France), Sevilla University (Spain), CEA-Bruyères-le-Châtel (France) and NSCL-MSU (USA) who are world leaders in these techniques.

Concerning neutron star studies, the IPN-Orsay theory group will link theoretical models tested with direct reactions on neutron-rich nuclei, together with the prediction of neutron stars observables. This group will also provide mean field calculations of pair form factors to be used in reaction models.

Using the Gogny force, the group from Bruyères-le-Châtel can also provide state-of-the-art mean-field calculations, in particular concerning the low-lying E1 strength, important for astrophysics and beyond. These mean field predictions can subsequently be linked to direct reaction observables through coupled channel or DWBA microscopic optical model potential calculations.

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

Our first aim will be to put in place a Management Board (MB) for the GASPARD project by November 2006. The MB will consist of one person from each of the institutes involved, with a Chair elected from within its membership for a defined period. The MB will be responsible for all aspects of the technical and financial management and will ensure that the GASPARD project achieves its objectives.

The first task of the MB will be to write an MoU for the R&D phase of GASPARD and ensure its signing by the collaboration. A first draft of the MoU will be produced by March 2007 with the signing taking place by June 2007. In the MoU, the R&D themes will be outlined, the responsibilities of the different institutes defined and the financial support structured. We envision that a Working Group (WG) for each theme will be established and that the WGs will report progress directly to the MB.

The MoU will cover the three years of R&D that will culminate in the building and testing of the GASPARD demonstrator. Provisions in the MoU will be made to extend the 3 year agreement by a further 3 years for the construction phase.

The construction of GASPARD will consist of **two stages**:

- R&D phase spanning 3 years leading to a GASPARD demonstrator covering 1/15 of the solid angle for both particles and gammas.
- Building phase spanning 3 years for the complete apparatus and system.

The R&D program will have the objectives of:

- Simulation studies for GASPARD: choice of detector, geometry and materials.
- Detection tests:
  - alternative telescope configurations (DSSD+SiLi+CsI choices, …).
  - mechanical design for the particle-gamma demonstrator module.
- Building and testing of prototypes and demonstrators for the front-end electronics under experimental conditions.
- Write-up of the final whitepaper for GASPARD.

The R&D phase will lead to the building of the demonstrator. Following this phase, the construction phase to build the full GASPARD array is envisioned to last a further 3 years.

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

The table below summarises the capital costs and manpower for the R&D and construction phases of GASPARD. A more detailed discussion is given in the attached Appendix.

| | Costs k€ | Manpower FTE |
|---|---|---|
| **R&D Phase** | | |
| Detectors PA & GA (appendix A) | **200** | **16** |
| Front End Electronics (appendix B.2) | **132** | **11** |
| **Construction Phase** | | |
| Detector (appendix A) | **1 700** | ***** |
| FEE and Data Acquisition (appendix B.1) | **413** | **1** |
| | | |
| **TOTAL** | **2 445** | **28*** |

* *Not yet fully defined.*

## ***Synergy with Other European Instrumentation Programs***

Given the broad range of requirements for the system outlined here, it is clear that the R&D for the present project will have significant overlaps with other LoIs. **A particularly important overlap is the scintillator-based Gamma Array (GA)**. Our aim will be to ensure that the requirements of the GA proposed here and those of scintillator-based gamma arrays proposed in other LoIs are **compatible** and thus only one **single GA** needs be built. Given the dynamic ranges for gamma and particle detection currently under consideration, this should be achievable. Other possible applications of the developments described here are in the LoIs for particle detection behind S3 and astrophysics.

Importantly, given the limited manpower and funds available within Europe, it is crucial that the developments be undertaken within synergy programs for the European radioactive beam facilities (GANIL, GSI, Legnaro). Presently a formal collaboration is being established between GANIL and GSI to identify synergies between the SPIRAL2 and NUSTAR experimental programs. This collaboration can be extended to include other laboratories. The synergies identified to date are: 1) Highly segmented Si detectors and thick Si detectors, 2) beam tracking devices, 3) Front-end electronics and data acquisition and 4) Gamma Arrays. Clearly including GASPARD within these programs is important.

## ***References***

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# Appendix: Preliminary Capital Costs and Manpower for GASPARD

We have based our very preliminary cost estimates on a system with 15 000 detection channels.

## A. Si and Calorimeter Detectors and Mechanics

We base our estimation on a conception of DSSD followed by thick padded Silicon detector and a gamma detector based on CsI scintillators:

| Item | Costs in k€ |
|---|---|
| DSSD & Si padded detectors | 700 |
| CsI and PM or avalanche PD | 500 |
| Mechanics | 500 |
| | |
| Total | 1,700 |

The costs and manpower for R&D for the Si modules are estimated to be 140 k€ and 12 FTE, respectively. The costs and manpower for R&D for the CsI modules are estimated to be 60 k€ and 4 FTE, respectively. These estimates include the costs and manpower to build a demonstrator that will cover 1/15 of the active area of GASPARD. We assume that engineering, design and construction as well as characterization and final detector mounting and cabling will be performed using existing infrastructure. We expect an additional 10 % increase of the costs in case spare modules are required. The FTE includes the simulation tasks.

**Total development costs: 200 k€**
**Total material costs: 1,700 k€**
**Total Manpower requirements : 16 FTE**

## B. Front End Electronics and Data Acquisition

The electronics and DAQ for the array has to handle both the Si recoil array and the surrounding calorimeter array for gamma and particle detection. These detector systems have a total of approximately 15 000 channels. The electronics comprises of two ASIC for Si readout (handling DSSD and PIN diodes) with at least 32 channels/chip. The cost assumes 32 channels/chip and any greater integration will produce some savings. The ASICs will be mounted with the pre-amp chips close to the detectors. The signal handling chip will be on cards which contain 10 ASICs (320 channels) multiplexed into a single output to an ADC card for readout. The multiplexer will use look-at-me logic to identify active channels rather than scanning all possible inputs. The ADC cards will have 8 inputs, each multiplexed down from 320 channels, so that each card handles 2560 channels, and 8 such cards will be needed in the full version. ADC cards will also contain an FPGA (Field Programmable Gate Array) and Ethernet readout (currently the best candidate is the Xilinx Virtex 4FX family of FPGAs with built in Ethernet MAC). The Gbit Ethernet fibre data links will transfer data through network switches to the DAQ system (PC farm). Mass storage is provided by the DAQ, as is a globally synchronised timestamp system. All data words will be time-stamped using a time distribution system. Software triggers will be built in the DAQ's processor farm. Other front end electronics for any smaller subsystems (e.g. neutron arrays, magnetic spectrometers) will be interfaced to the DAQ using an interface card which timestamps the data using the same time distribution system. This mechanism allows conventional triggered data to be merged with the free running time-stamped data from parts of the system which will use software triggering. In this way the array will have a coherently integrated, but not uniform, system of front end electronics and DAQ.

***B.1.1 ASIC capital cost:***

Considering an ASIC with 32 channels of preamp, shaper, discriminator, sampler, TAC and multiplexer, then for 15 000 channels we require 480 ASICs.
Consider 500 chips/wafer (100 $mm^2$ each) then we need 1 wafer – buy 2 for spares. Assume that the packaging cost is €50 each chip and calculate cost for packaging all 3 wafers.

| | |
|---|---|
| Submission before final production | 60 k€ |
| Mask set: | 55 k € |
| 3 wafers: | 15 k € |
| Packaging: | 75 k € |
| **Total for 1500 ASICs:** | **205 k €** |

***B.1.2 ASIC board capital cost:***

Assume 10 chips/board plus some passive components and one intelligent chip (DSP or FPGA). Then we need 48 boards (60 including 12 spares). The NRE is split across 60 units: 5000/60 € ~ 85 € per board.

Components (except ASICs) 250 €
PCB cost 150 €
NRE costs (1/60 share) 85 €
Assembly cost 150 €
Total unit price 635 €
**Price for 60 units = 38 100 k€**

***B.1.3 ADC board capital cost:***

Assume that we bring ASIC signals from 1 ASIC board into a single ADC and that we mount 8 ADCs per ADC card then we need 8 ADC cards for 60 ASIC cards (includes spares). The NRE is split across 8 units: 5000/8 € ~ 625 € per board. Include one intelligent chip (FPGA) in each board to interface via XPORT to Ethernet, for control and Gbit Ethernet for readout)

Components 300 €
PCB cost 150 €
NRE costs (1/8 share) 625 €
Assembly cost 150 €
Total unit price 1225 €

**Price for 8 units = 9 800 k€**

***B.1.4 Total Capital cost for array FEE:***

| | |
|---|---|
| ASIC: 1,500 units at a total cost of | 205 000 k€ |
| ASIC board: 60 units at total cost of | 38 100 k€ |
| ADC board: 8 units at a total cost of | 9 800 k€ |
| 3 racks with 7 crates and power | 40 000 k€ |
| HT and detector power units | 120 000 k€ |
| **Total capital costs for electronics:** | **412 900 k€** |

***B.1.5 Manpower:***

Manufacturing will be undertaken in industry, not in labs so all manufacturing manpower is included in capital costs. Some low level of manpower is needed for supervising the contracts and liaising with manufacturers. This is less than **1 FTE**.

## B.2 Development costs for array FEE:

***B.2.1 ASIC prototypes:***

Assume that we need 2 prototype iterations of a 100sq mm chip on AMS 0.35u process then the cost of each iteration is about 60,000 €. So ASIC development cost is 120 k€

***B.2.2 Electronics prototypes:***

ADC and ASIC cards: one off using costs listed above with full NRE: approx 6k € per card for ADC and ASIC card: 12 k €.

***B.2.3 R&D Manpower:***

**B.2.3.1 ASIC Manpower:**

Assume that we use 2 engineers full time for 3 years: 6 FTE.

**B.2.3.2 Other Electronics Manpower**:

Assume that we use 2 engineers full time for 1 year to make the ASIC and ADC boards: 2FTE

Assume that we use 1 engineer (hardware or maybe software) full time for 1 year to program the intelligent devices (FPGAs) on the ADC and ASIC boards: 1FTE.

**B.2.3.3 Software Manpower:**

Assume that we use 2 people for 1 year to program the slow control and the GUI: 2FTE.

**Total Manpower for development (R&D)** **11 FTE**

***B.2.3.4 Total development cost:***

| | |
|---|---|
| ASIC development | 120 k€ |
| Electronics prototype | 12 k€ |
| **Total Development** | **132 k€** |

**Manpower** **11 FTE**

## C. Summary of capital costs and manpower for GASPARD.

| | Costs k€ | Manpower FTE |
|---|---|---|
| **R&D Phase** | | |
| Detectors PA & GA (appendix A) | **200** | **16** |
| Front End Electronics (appendix B.2) | **132** | **11** |
| **Construction Phase** | | |
| Detector (appendix A) | **1,700** | ***** |
| FEE and acquisition (appendix B.1) | **413** | **1** |
| | | |
| **TOTAL** | **2,445** | **28*** |

** Not yet fully defined.*