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THE PARIS PROJECT*

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The PARIS project is an initiative to develop and build a high-efficiency gamma-calorimeter principally for use at SPIRAL2. It is intended to comprise a double shell of scintillators and use the novel scintillator material $LaBr_3$(Ce), which promises a step-change in energy and time resolutions over what is achievable using conventional scintillators. The array could be used in a stand-alone mode, in conjunction with an inner particle detection system, or with high-purity germanium arrays. Its potential physics opportunities as well as initial designs and simulations will be discussed.

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1. Introduction

Nuclear reactions induced by beams of exceptionally high intensity as will be available in the near future at SPIRAL2 facility [1] in GANIL (France), will allow us to greatly further our understanding of the diverse behaviour of the atomic nucleus, and address in detail some of the longstanding open questions for this field. Exotic compound nuclei under extreme conditions of excitation energy and/or angular momentum can be reached by means of fusion reactions involving neutron-rich SPIRAL2 beams. The range of available beams will make it possible to fine tune the initial conditions in terms of nuclear composition and states which are populated. This will be of great benefit in the study of single-particle and collective phenomena and their evolution with temperature and rotation. It will also permit the study of nuclear dynamics from the astrophysical to the multi-fragmentation energy domain. Moreover, very intense stable beams from the future LINAG facility [2] in GANIL will allow us to investigate neutron-rich nuclei either via deep-inelastic or transfer mechanisms. In this way, nuclear structure at the drip-line can be studied in detail to provide the strongest constraints on the interactions that govern the nuclear medium far from stability. The energy, multiplicity and angular distribution of γ-rays de-exciting the nuclei of interest will be a sensitive probe across all of the physics topics discussed above. Such future experiments will, however, present great challenges in extracting events from channels with tiny cross-sections from a high background due to the activity of the beam. In order for the ambitious future physics program to succeed, next-generation detection systems will be needed.

The PARIS (acronym for *Photon Array for studies with Radioactive Ion and Stable beams*) collaboration [3], founded a couple of years ago, aims to build an innovative γ-array, playing the role of an energy-spin spectrometer, a calorimeter for high-energy photons and a medium-resolution γ-detector. The current design envisages a device using two shells: the most advanced scintillator technology for the inner volume — offering simultaneously high efficiency and relatively good energy resolution; and more conventional techniques for the outer shell.

2. Physics cases

The PARIS project draws on a wide section of the nuclear physics community with a broad range of physics interests. The primary goal is to use PARIS at the SPIRAL2 facility, to study the properties of hot rotating exotic nuclei produced in the fusion-evaporation reactions by means of the γ-decay of the GDR. In addition, the installation of the array at the secondary target position of the Super Separator Spectrometer (S^3) [4] — profiting from the future LINAG beams — is expected to be very promising for γ-ray spectroscopy. Moreover, PARIS could be used for the g-factor and quadrupole moments measurements, as well as for nuclear astrophysics experiments. The main physics cases considered are described briefly below.

2.1. The Jacobi shape transition and GDR studies of hot and rotating exotic nuclei

The nuclear Jacobi shape transition corresponds to a change at high angular momenta from oblate to triaxial and very elongated prolate configurations. The liquid drop LSD model [5, 6] predicts it to appear in many nuclei in the liquid drop regime and is considered as a gateway to hyperdeformed shapes.

The giant dipole resonance (GDR) line-shape is a very sensitive signature of this phenomenon: its strength function gets split according to the deformation of the system and a "giant back-bend" in the rotational frequency occurs at the highest spins (see Fig. 1). So far, firm evidence of a Jacobi transition has been found in light- and medium-mass nuclei only [7–9], and a preferential feeding of highly deformed structures by the GDR low-energy component has been observed in a few cases [10,11]. The difficulty of studying these phenomena in detail is mostly related to the narrow range in angular momentum L and excitation energy E^* in which it occurs for light systems, and to the proximity of fission for heavy systems. The GDR profile has therefore to be extracted properly and the multiplicity M and energy sum Σ of the statistical gamma-rays has to be determined accurately, from which the (E^*, L) entry point is deduced. Favorable conditions are expected

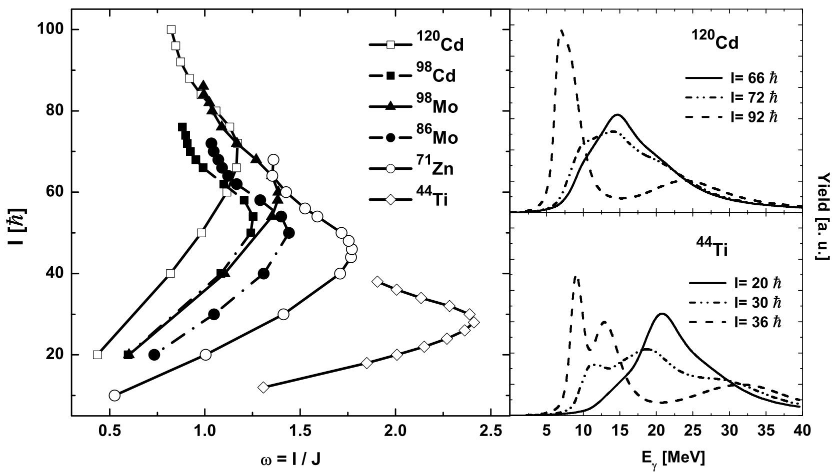

Fig. 1. (Left) A giant-backbend plot (spin *versus* rotational frequency) for some nuclei. (Right) GDR strength function for 3 different spins for ^{44}Ti (bottom) and ^{120}Cd (top). Data based on the LSD model calculations.

to be met in exotic, neutron-rich nuclei, accessible via fusion-evaporation with the advent of SPIRAL2 beams, as shown in Fig. 1. As an example, we consider the compound nucleus ^{120}Cd, which can be produced at very high angular momentum, almost reaching 100 $\hbar$, in inverse kinematics by the SPIRAL2 ^{94}Kr beam impinging on ^{26}Mg target. Several other nuclei predicted to exhibit a Jacobi transition either will be within reach by the use of radioactive beams, or are already accessible with stable beams (*e.g.* ^{44}Ti via ^{12}C+^{32}S reaction). In this type of experiment one will require a coupling of the 2π PARIS array to the AGATA Demonstrator and for example to the Recoil Filter Detector RFD [12].

Theoretical calculations [13] predict also that many nuclei possess a temperature interval where rotation generates a prolate spheroid rotating along its symmetry axis (*i.e.* non-collective prolate) in contrast to that caused by the Jacobi transition. 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 most likely isospin-dependent. A tri-critical point in the (E^*, L) diagram — around which non-collective oblate, non-collective prolate, and collective tri-axial or oblate shapes coexist — is thus expected. Beside its line shape, the angular distribution of GDR γ-rays constitute a clear signature of the nature of the state. To explore such shape phase space transitions, the differential technique [14, 15] has been found to be very powerful: neighbouring compound nuclei are produced via different reactions in order to select a well-defined region in the (E^*, L) diagram. Yet, to fully exploit the technique, a particularly efficient and accurate multiplicity and energy sum filter is mandatory.

In addition to its shape dependence discussed above, the width of the GDR depends on temperature, angular momentum and presumably isospin. Fine structure effects and local shape transitions are difficult to unambiguously pinpoint experimentally, and further understand theoretically, if E^* and L remain un-controlled. To get insight into this puzzling interplay, the influence of temperature and spin have to be disentangled. That calls for a precise measure of the GDR profile and accurate M and Σ data. Once excitation energy and angular momentum effects are resolved, even more exotic phenomena such as the appearance of soft dipole modes (Pygmy Dipole Resonances) in hot, neutron rich systems can be investigated.

The study of nuclei under extreme conditions, namely the question about the highest excitation energy a nucleus can sustain, is revealing of the transition from a semi-quantal low-energy regime — dominated by collective excitations and light-particle evaporation — to a statistical high-energy regime — with break up of the system into small pieces. When two ions collide, the compound system needs some time to equilibrate all its degrees of freedom. At very high energy, there is not enough time to develop a coherent collective behavior such as a breathing, vibration or rotation. Correlations thus remain local and lead to the pre-formation of fragments inside the system. Repulsive Coulomb forces finally lead to a multi-fragmentation of the system. The development of "local sub-structures" implies the disappearance of the concept of the mean field. The GDR being a good indicator of the cohesion of an excited system, its disappearance and the saturation of its width, observed [16] around 3–5 MeV temperature depending on the mass, might be interpreted as a loss of collectivity and an evidence of a transition towards a chaotic regime. Nevertheless, the experimental information is very scarce and vividly debated. To unambiguously determine whether the potential saturation of the GDR width has to be linked to the on-set of a multi-fragmentation regime, observables typical for the low- and high-energy regime have to be measured simultaneously over a wide range of temperature, and the width of the GDR profile has to be extracted with high accuracy, requiring high efficiency and good resolution. In addition a coupling to the efficient charged particle detector (*e.g.* INDRA, FAZIA or a dedicated array) is mandatory.

2.2. Heavy-ion radiative capture and reaction dynamics

Heavy-ion radiative capture is a rare process due to the high Coulomb barriers and overwhelming competition from particle emission. Yet, unexpectedly large cross-sections have been observed in some cases. They have been related to giant resonance enhancement of γ-ray decay widths, involving specific doorway states. A famous example is the radiative capture of ^{12}C by ^{12}C [17]. The precise nature of the entry capture state could not be firmly determined yet. Nonetheless, the idea about doorway states based on a molecular structure of the decaying system has been recognized as very valuable. These states seem to feed preferentially specific structures, namely highly deformed rotational bands in ^{24}Mg. Usual statistical considerations involving many levels do therefore not hold any more; the system relaxes through a few specific states. Microscopic cluster approaches based on a many-body Hamiltonian and the Generator Coordinate Method have shown very pertinent in studying this phenomenon: they predict bands based on a ^{12}C–^{12}C "molecular" configuration in which wave-function sizeably overlaps with those of highly deformed states in ^{24}Mg. To obtain more information about specific paths, both the energy and angular distribution of the highly energetic γ-rays that de-excite the corresponding states have to be measured with good resolution. In addition, to isolate properly the capture states, the measurement of the energy sum is needed. Radiative capture is proposed to be investigated in detail for the ^{12}C+^{12}C test case. From the theoretical point of view, identical bosons in the entrance channel minimize complex aspects, while on the experimental side previous studies still had to face poor statistics and restricted sensitivity, precluding firm conclusions to be established. Since for such an experiment high efficiency and wide angular coverage are primordial, the full PARIS available at the time is required. In addition, a powerful heavy-ion spectrometer is highly desirable to select properly the entry capture state and correct precisely for Doppler effects.

The dynamical evolution of an excited compound nucleus as produced by a given entrance channel strongly depends on the viscous nature of nuclear matter. The latter implies a dissipation of energy between the collective and intrinsic degrees of freedom of the system. Due to the variety of shapes, excitation energies and angular momenta explored by the nucleus along its decay, no consensus emerges yet about the magnitude of this energy dissipation and its likely dependence on deformation, E^* and L. As a typical large-scale amplitude collective motion, fission stands for an excellent probe of nuclear viscosity. Of paramount interest is the time scale of the process, straightforwardly related to the underlying dynamics. Light-particles and GDR γ-rays have been shown to establish pertinent clocks of fission time scales. Yet, both data sets still disagree about the value extracted for the viscosity strength. To understand this discrepancy and exploit further these powerful tools, the predicted respective influence of temperature and angular momentum on dissipation phenomena has to be resolved first. To do so, the GDR decay has to be precisely sorted out according to excitation energy and spin *i.e.* it has to be measured in coincidence with Σ and M. Similarly, the GDR clock can be used to investigate the dynamics in the entrance channel, namely the competition between fusion and quasi-fission, which strongly hampers the synthesis of super heavy elements.

2.3. Gamma-spectroscopy close to the neutron drip-line using reactions induced by in-flight radioactive nuclear beams at S^3

The vanishing of the well-known magic numbers far from stability towards the neutron drip-line [18] and the existence of an island of inversion [19] is still controversial. Nuclear level schemes are of primary importance for determining the existence of shell gaps and understanding the underlying single-particle structure.

Neutron-rich species can be populated efficiently in multi-nucleon transfer and deep inelastic reactions taking profit from very intense LINAG stable beams in an in-flight mode using the Super Separator Spectrometer (S^3) being developed for SPIRAL2 and a high-power rotating target. Provided reasonable rates and energies above the barrier for the produced beams, a large variety of secondary reactions such as inelastic scattering, transfer, deep-inelastic and fusion-evaporation reactions can be explored to form even more exotic nuclei which level scheme is still virgin. In the very near future, cross-sections using one of this production method, namely deep-inelastic collisions close to 0°, will be measured and compared to model calculations. From that detailed investigation, the possibility of measuring the energy of the 2^+ state in ^{78}Ni and check the effectiveness of its double magicity will be evaluated. The study of the structure of neutron-rich nuclei produced this way calls for a very efficient device according to the small cross-sections involved and the few states populated.

The PARIS array is proposed to be installed at the secondary target position of S^3 separator for measuring in-beam gamma rays emitted from secondary reaction products with large neutron to proton excess. The S^3 will be used to select a given secondary beam that further interacts in a second target leading to the very exotic species of interest. PARIS detectors in conjunction with AGATA and EXOGAM2 detectors could be used to measure the spectroscopy of these exotic nuclei which are identified with the second half of S^3. This type of experiment will be certainly one of the first that will be performed with the high intensity stable ion beams from LINAG.

3. PARIS specifications and preliminary designs

From the survey of physics cases described above, the most crucial requirements for the device to be constructed become more clear. The energy resolution shall be of the order of (3–5)% up to γ-ray energies around 10 MeV and even better for photons up to 40 MeV (this implies use of $LaBr_3$(Ce) crystals). The desired accuracy of the entry point location in the (E^*, L) space demands a resolution of about 5% for the energy sum and of about $\Delta M/M = 4$ for the γ-ray multiplicity. These numbers imply high efficiency, wide angular coverage and sufficient granularity. High efficiency is essential for all the physics cases due to low cross-sections and/or overwhelming background.

Considering the photopeak efficiency, the device should cover as much as possible of 4π. Together with granularity, this feature is even more important when angular distributions have to be measured. Good timing properties are crucial as well: the time-of-flight resolution has to match the sub-nanosecond level in order to remove unwanted background. Scintillator materials of new generation seem to cope with all these requirements. For γ-ray energies above about 2 MeV, relatively low multiplicities and fast beams — as it is often the case for spectroscopy studies of exotic light neutron-rich nuclei, $LaBr_3$ scintillators compete with Ge detectors in terms of resolution while being more efficient, what is advantageous for low cross-sections and/or beam intensities.

Considering the excellent energy resolution, it is crucial not to spoil it. For that, the Doppler broadening should be kept as small as possible (less than 3%) for most of the physics cases to be addressed: it implies a well suited segmentation. Increasing the segmentation has also the advantage of reducing pile-up effects which reduces the error in extracting the multiplicity of the γ-ray cascade. On the other hand, one should also avoid a too large segmentation so that too many segments need to be combined to reconstruct the γ-ray energy. In addition, the data processing of highly segmented devices requires complicated algorithms to reconstruct properly the different kind of events.

The crystal depth impacts directly on the full absorption probability. Because such new material is very expensive, one may not be able to build a device as deep as would be required by the different physics cases to be addressed, in particular for photons up to 40 MeV. The original PARIS proposition is to have two layers of scintillators, the first one being composed of $LaBr_3$, the second one of another less expansive material. In such a case, the first shell is used as a sum-spin spectrometer while the second one is devoted to high-energy γ-rays. One of the crucial question to be addressed by realistic simulations is to prove that building such a device makes sense. Indeed, the first layer is likely to absorb also high-energy photons.

Nearly all the physics cases, discussed in Sec. 2, require ancillary detectors in addition to the PARIS array. These are namely *(i)* heavy-ion spectrometers for selecting the mechanism and — in some cases — for fully identifying the reaction product as well as determining its velocity as suited for Doppler correction, *(ii)* light-particle detectors to reconstruct the kinematics of the process and sometimes *(iii)* high-resolution Ge detectors (*e.g.* EXOGAM2 or AGATA) to complement PARIS when pursuing discrete low-energy γ-rays. This mandatory coupling to various other instruments necessitates a versatile device.

In order to answer these questions, a GEANT4 package for PARIS has been developed and has been used to study different configurations (see Fig. 2). An "ideal" geometry, composed of one or two concentric spheres, and more realistic geometries, spherical-like and cubic-like, were investigated and helped to establish the best performance. It is also a perfect benchmark to understand how the various γ-rays are absorbed and it gives then vital information for the reconstruction algorithms.

These extensive simulation studies indicate that an individual element should have an opening angle that does not exceed 20°, a very good value being 6°. It corresponds to a geometry with a few hundreds of elements. The length of the $LaBr_3$ crystal constituting the inner shell should be between 5 and 10 cm, while the length of the BaF_2 or CsI crystals in the outer shell — at least 15 cm. The inner radius of the whole array shall be between 15

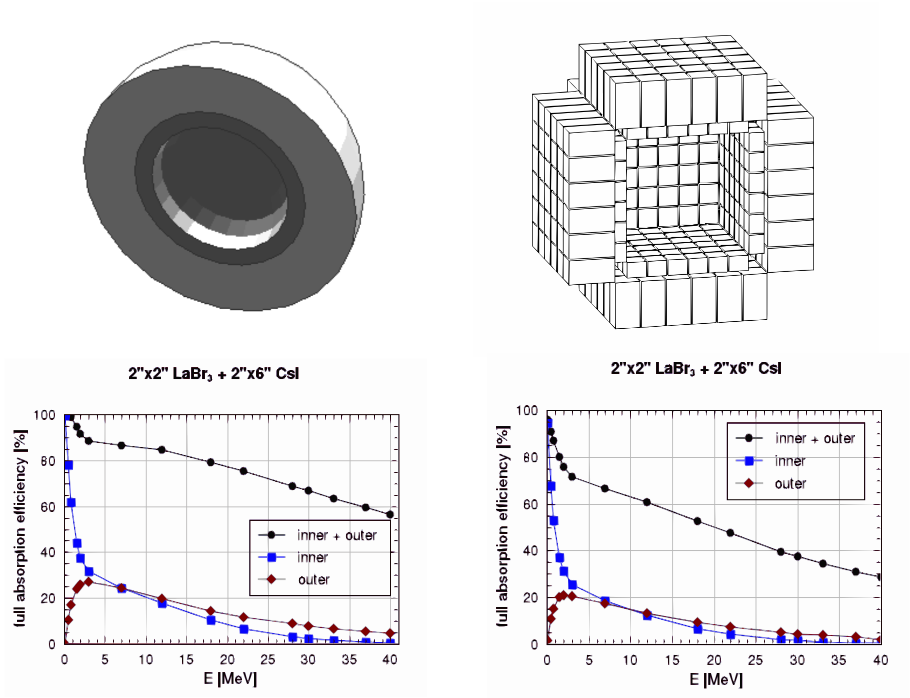

Fig. 2. (Upper row) Two geometries of the two-shell gamma-calorimeter, spherical and cubic, used in GEANT4 simulations. The inner (outer) shell, made of $LaBr_3$ (CsI), is 5 cm (15 cm) long respectively. In the figure a part of the array was removed to better see the inner part. (Bottom row) Corresponding total efficiency: full-energy peak efficiency for inner shell (squares), for outer shell (diamonds) and for the efficiency in the case of the adding back signals both from inner and outer shell (circles).

and 25 cm. Studies about clustering methods and reconstruction algorithms have just started and should provide the last results which would help to design the best configuration for the PARIS array.

As far as the individual elements of the two-shell array are concerned, there are three possible scenarios differing by the method of the signal read-out: both inner and outer scintillator coupled to their own photomultiplier; the inner scintillator read by APD (allowing the radius of the outer shell to be minimised), and a "phoswich" type in which $LaBr_3$ is coupled directly to CsI(Na) and both signals are read by common PMT. The possibility of the last scenario has still to be investigated.

Taking all these factors into account, a number of possible mechanical design scenarios emerge. Some of them, both spherical- and cubic-like, for 200 elements (each consisting of 2 crystals), are shown in Fig. 3.

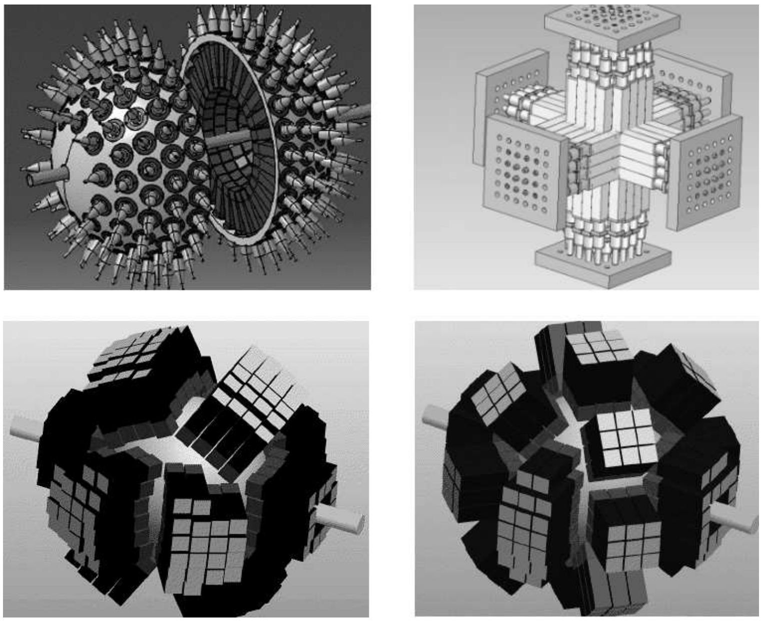

Fig. 3. Possible designs of spherical and cubic geometries for 200 elements, each consisting of 5 cm long $LaBr_3$ in front and 15 cm conventional (CsI(Na) or BaF_2) crystals at the back.

4. Outlook

In the immediate future, the PARIS collaboration is going to test all considered detector types and build a PARIS prototype, which would consists of few elements. After testing its performance the decision on the final choice for PARIS will made. This, together with the results of more realistic GEANT4 simulations will lead to the decision on the final PARIS geometry.

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