$(NA)^2$STARS Project

Neutrinos, Applications and Nuclear Astrophysics with a Segmented Total Absorption with higher Resolution Spectrometer.

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I. Proposal's context, positioning and objective(s)

The fundamental physics focus of this project is the study of the nuclear beta decay process in nuclei far from stability using the Total Absorption Gamma-ray Spectroscopy (TAGS) technique, by building a Total Absorption Spectrometer (TAS) of second generation. The new instrument, called STARS (Segmented Total Absorption with higher Resolution Spectrometer), will ally efficiency to a higher segmentation and energy resolution than the existing TAS thanks to the adjunction of 16 $LaBr_3$ crystals. The two segmented TAS existing in Europe that will benefit from this upgrade are the DTAS detector shown in Fig. 1 (DESPEC TAS, 18 NaI crystals [1]) and the *Rocinante* detector shown in Fig. 2 (12 BaF_2 crystals [2]). The proposed physics program is presented in the next paragraphs.

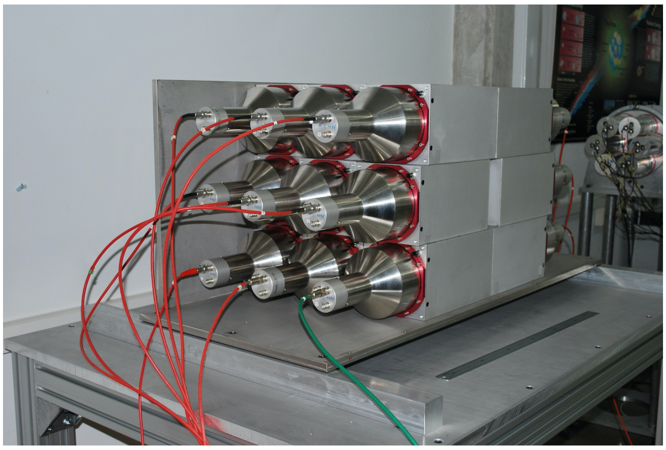

Fig. 1 DTAS spectrometer constituted of 18 NaI modules [1].

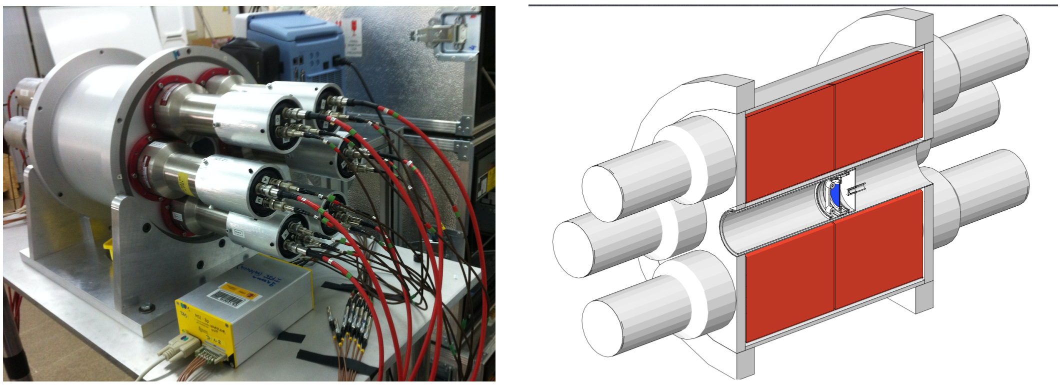

Fig. 2 Left: Rocinante TAS constituted of 12 BaF_2 detectors. Right: Inside view of the geometry of the Rocinante detector (GEANT4 simulation) [2].

a. Physics Context, objectives and limitations

Physics Context

The TAGS technique is the best suited to access experimentally the beta strength, a microscopic observable providing a new insight in the nuclear structure of the most exotic nuclei. A knowledge of the beta strength provides constraints on the theoretical microscopic models complementary to the ones brought by integral observables such as half-lives and Pn-values, very important ingredients in the r-process calculations. The distribution of the beta strength as a function of the energy is a sensitive test of nuclear theoretical models and hence could open the door to a deeper understanding of residual interactions between nucleons.

Before the 1990s, high resolution gamma-ray spectroscopy through the use of germanium detectors was the conventional detection technique used in beta-decay studies for γ-ray measurements. It offers excellent energy resolution but an efficiency which strongly decreases at high energy and usually limited acceptance. As direct consequences, weak γ–ray cascades are likely difficult to detect and the decay scheme of the daughter nucleus may be incomplete. There is a danger of overlooking the existence of beta-feeding into the high energy nuclear levels of daughter nuclei especially with decay schemes with large Q-values. This phenomenon is called “Pandemonium effect” highlighted by Hardy in 1977 [3].

This problem can be circumvented using the total absorption gamma spectroscopy technique, where a different approach is taken. The method involves a large 4π scintillation detector and is based on the detection of the full deexcitation gamma cascade for each populated level, rather than detecting the individual γ-rays as illustrated in Fig. 3. The power of TAGS to find the missing beta intensity has been demonstrated in a number of papers [4-18]. Fig. 4 shows an example where the B(GT) distributions (deduced from the beta feeding) for the decay of the ^{150}Ho 2^- state to levels in ^{150}Dy measured with the Cluster cube [17] and with a Total Absorption Spectrometer (TAS) [18] are compared. The Cluster cube was an array of six Euroball Ge cluster detectors in compact geometry, equivalent to 42 individual Ge detectors and had an efficiency of 10.2(5) % at a gamma-ray energy of 1332 keV. This value represents a very high efficiency value even compared with today gamma-ray high resolution spectrometers. The figure shows clearly the importance of both types of measurement. In the Ge spectrum 1064 gamma rays are found and the coincidences between detectors allowed the construction of a decay scheme with 295 levels in ^{150}Dy. Inspection of the total absorption spectrum reveals that the Ge array loses sensitivity as a function of excitation energy in the daughter nucleus when compared with the TAGS and the ability to determine the feeding or beta intensity distribution diminishes. Once converted into B(GT) strength it was concluded that 50% of the total strength was lost compared with the TAGS measurement. The Ge measurements are essential, however, in order to get details of the decay scheme and the fine structure of the populated resonance. Even with an excellent array such as the Cluster cube the distortion of the beta intensity distribution leads to a systematic error in the average beta and gamma energies determined for the decay. Looking at a wider picture many such entries in the international databases, that rely solely on measurements with Ge detectors, will suffer from the Pandemonium systematic errors. This means that the results cannot be relied on for certain applications. The solution to this problem resides in the use of TAGS.

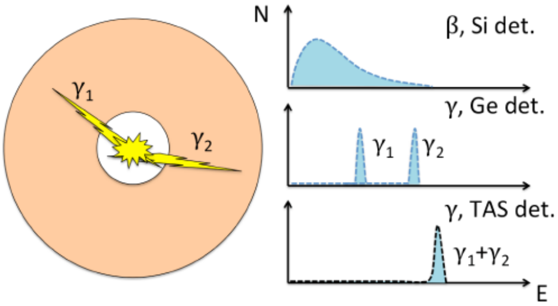

Fig. 3. Schematic picture [19] of how a simple beta decay towards a state which deexcites through two gamma-rays (like ^{60}Co source) is seen ideally by different detectors used in beta decay studies [18]. Left panel, representation of a total absorption detector, right panel, ideally detected spectra with a beta dectector (a silicon detector), a Ge detector and a total absorption detector after the same decay.

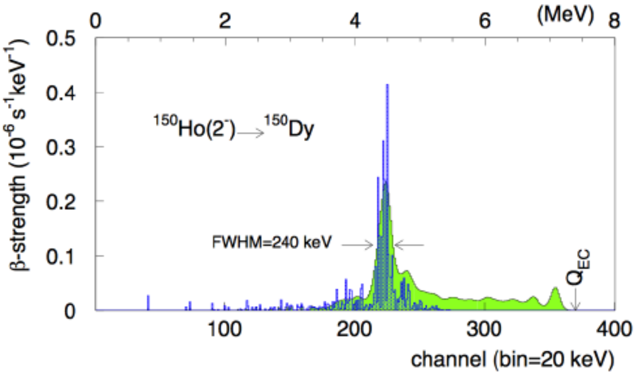

Fig. 4. Comparison of the beta strength deduced from the high resolution measurement of the beta decay of the 150Ho 2- isomer using the cluster cube setup [17] (shown in blue) with the strength obtained from a total absorption measurement [18] (green). The measurements were performed at the Mass Separator at GSI by the Valencia group, partner of this project.

The access to beta strength in exotic nuclei is challenging, since the TAGS method requires a minimal knowledge of the structure of the nucleus under study. This actual limitation of the method could be lifted with the realization of an advanced Total Absorption Spectrometer (TAS) with improved efficiency and energy resolution thanks to the adjunction of a set of $LaBr_3$ crystals. A possible arrangement of 16 $LaBr_3$ crystals in the middle of the DTAS is shown in Fig. 5. These 16 $LaBr_3$ modules will also allow to upgrade the Rocinante TAS (see. Fig. 2). Depending on the experiment, one or the other TAS could be used depending on the most adapted detection properties. The modularity of the advanced TAS will offer a great flexibility in the possible arrangements of the crystals. **We propose to push our physics program further with the development of such advanced TAS.**

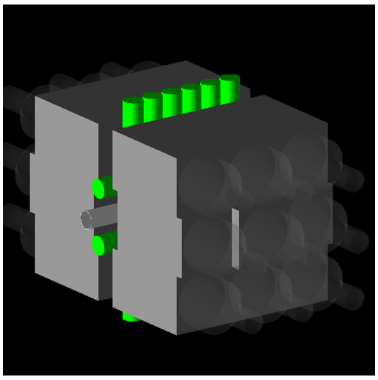

Fig. 5: possible arrangement of 16 LaBr3 modules between the two halves of the DTAS spectrometer simulated with the GEANT4 software [ref].

Physics Program

The scientific advances will concern nuclear structure and astrophysics, and neutrino and reactor physics. The research objectives span a wide physics program that is susceptible to gather a wide international community of users around the proposed advanced TAS (called STARS for Segmented Total Absorption with higher Resolution Spectrometer).

We list in the paragraphs below, the actual scientific and technical barriers associated with each physics topics that we want to advance significantly through this project and explain how the use of the STARS would allow to lift these barriers. Some of the foreseen experiments are not yet feasible at the GANIL facility but we propose to perform a part of this program there.

Nuclear structure objectives

The beta strength distribution and the deduced B(GT) provide very valuable information on the structure of the nuclei under study. The TAGS collaboration has studied the beta decay properties of exotic nuclei both on the neutron-rich and neutron-deficient sides of the nuclear chart for more than two decades.

The TAGS technique has been used successfully in the **study of neutron-deficient nuclei** with the physics program carried out at ISOLDE with the TAS called *Lucrecia* [5-9]. **In a series of experiments it was demonstrated that the beta strength distribution measured with the TAGS technique in exotic nuclei could bring valuable information on the sign of the deformation of the ground state of a nucleus, when compared with theoretical models.** This research program was aimed at determining the ground state shape of the neutron-deficient nuclei ^{74}Kr [6], ^{78}Sr, ^{78}Rb and ^{76}Rb [7], to study the beta decay of the N=Z nuclei ^{76}Sr [5] and ^{72}Kr [8] and to study ^{192,190}Pb isotopes [9] and more recently ^{186}Hg [10]. In all the above-mentioned cases the beta strength distribution and the deduced B(GT) provided very valuable information on the structure of the nuclei under study.

Beta strength distributions of neutron-rich nuclei have been measured as well. In this case, there is a strong overlap between the nuclear structure motivations and nuclear astrophysics, for instance with the r-process, and reactor applications (neutrino and reactor physics). More details on the previous TAGS results are provided in the paragraphs associated to these physics goals below. The interested reader can also refer to [20] for a recent review.

In the future, it is particularly important to perform this kind of measurement near the unstable doubly-magic nuclei ^{100}Sn, ^{132}Sn and ^{78}Ni. These three regions have been the object of three Letters of Intent to the SPIRAL2 facility in 2011 by the TAGS collaboration [21].

- **Nuclei close to doubly-magic ^{100}Sn**

Experiments are foreseen at Riken (Japan) and SPIRAL2-DESIR [21,22] on n-deficient nuclei.**There are several reasons why the region around ^{100}Sn is of great interest:** the shell structure of nuclei in the vicinity of the Z=N=50 doubly-closed shell, the possibility of studying the heaviest accessible particle bound N=Z nucleus and the evolution of the nuclear structure when approaching ^{100}Sn, the study of the quenching of the Gamow-Teller resonance [23,24] and the astrophysical relevance of decays in this region for the rapid proton-capture process (see for example [25,26] and references therein). **The advanced TAS proposed in this project will be ready for the start of SPIRAL2 S3-LEB or DESIR so that this top-level instrument could be coupled with the most intense neutron-deficient beams of the ISOL facilities worldwide, promising unique results.**

- **Nuclei close to doubly-magic ^{132}Sn**

The situation in ^{132}Sn and nearby nuclei is completely different from the super-allowed Gamow-Teller decay of ^{100}Sn where the full strength is expected to be concentrated in a single state, since in ^{132}Sn the major shell from 50 to 82 is occupied on the neutron side and completely empty on the proton side. This means that there are many possible allowed transitions. Part of this strength, which is highly fragmented, is inside the Q-beta window and part of it outside. To be able to compare the real beta strength in the beta window with theoretical model would be very important to validate these models in this region of the nuclide table, also in view of the relevance of more exotic nuclei for the astrophysical r-process. **Up to now the region near ^{132}Sn remains unexplored using this technique.** High energy resolution experiments start to release their first results in this region and have reported excited states at high excitation energy [27-29]. Their experimental identification is essential and TAGS studies are therefore mandatory to better quantify previous observations and to provide beta strength values free from the Pandemonium effect. In this region, nuclear structure and nuclear astrophysics motivations overlap (with the r-process and the probe of low-lying collective modes). Numerous isomers can be found and scarce knowledge on the structure of daughter nuclei, which is a pre-requisite to allow TAGS measurements. In addition in the case of neutron-rich nuclei, large Pn values can be found and delayed neutrons constitute then a large contamination of the gamma spectrum. **Here again, the many advantages of the STARS (improved energy resolution of the $LaBr_3$ modules, γ-n discrimination and possibly γ–γ correlations) will allow to reach more exotic nuclei with the TAGS technique and gain more information on their nuclear structure.**

- **Nuclei close to doubly-magic ^{78}Ni**

Beta decay properties in the region of neutron-rich nuclei close to Z=28 and N=50, in particular half-lives $T_{1/2}$ and neutron emission probabilities P_n, are rather sensitive to nuclear structure effects. It is expected that the interplay between allowed Gamow-Teller (GT) and first forbidden (FF) transitions will have a significant impact on these properties [30,31]. In a simple picture, from the available ocupied and empty orbitals for nuclei with Z>28 and N>50, one expects that the contribution of high-energy FF transitions becomes significant, even dominant, with respect to low-energy GT transitions. This should be reflected in changes of the beta-strength distribution, and consequently on $T_{1/2}$ and P_n which are integral related quantities. Experimental information on half-lives and neutron emission probabilities around ^{78}Ni has extended considerably into more exotic regions in recent years [32,33]. There is also a number of recent theoretical calculations [34-37], all of them including FF transitions, aiming at a global prediction of these quantities for nuclei without experimental data. The focus of these is on its use in calculations of heavy element nucleosynthesis through the rapid neutron capture process. However a comparison reveals that there are large discrepancies between calculation and experiment that do not show a clear trend. Even more, large variations between different models are observed.

Full beta-strength measurements using the TAGS technique are needed in order to shed light on the situation. The level density in nuclei in the vicinity of doubly-magic ^{78}Ni is low, and the nuclear statistical model likely not applicable. **In this respect the segmented character of DTAS and its enhancement with high energy resolution modules proposed in this project will be key features in order to identify levels and de-excitations and extract accurate beta-strength distributions. A number of relevant nuclei can be studied at the DESIR/SPIRAL2 facility.**

Nuclear astrophysical objectives

Some of the nuclear structure physics objectives presented above have a strong overlap with nuclear astrophysics objectives, either for the neutron-deficient than for the neutron-rich nuclei.

- **The astrophysical rp-process**

We propose studies in the A~80 region that is of relevance for the astrophysical rapid proton capture (rp-) process [38]. The astrophysical rp-process is a succession of proton captures and beta plus decays along the proton drip-line thought to be at the origin of the neutron deficient heavier elements. It would occur on the surface of neutron stars accreting H and He from a companion star provoking thermonuclear flashes called X-ray bursts (XRBs) [39,40]. Observations of these phenomena have prompted numerous studies in theoretical astrophysics and experimental nuclear physics since their discovery several decades ago (for a recent review see [41]). The light curves exhibited by such XRBs, as well as the final composition of the ashes that remain at the surface of the neutron star after the explosion, depend upon the influence of specific beta decays. While the decay properties at high density and temperature in rp-process sites may be very different from terrestrial conditions, proper reproduction of decay properties in terrestrial conditions is a first requirement for models used to predict the same properties under rp conditions. To test such nuclear models, experimental beta-decay data of some key cases may be of paramount importance. **In this context we propose here to measure the decay of the beta decays of ^{84}Mo, ^{88}Ru, ^{92,94}Pd with the TAGS technique. These studies are also relevant from the perspective of nuclear structure. The future clean beams provided by S3 to the DESIR hall combined with the STARS will make the study of these nuclei possible.**

- **The astrophysical rapid neutron capture process**

The **astrophysical rapid neutron capture process, the r-process**, is responsible for the production of around half the elements heavier than iron. The kilonova observed in association with the GW170817 gravitational waves gave direct evidence that the r-process takes place at least in neutron star mergers [42]. Recently, several sensitivity studies [43] indicate that the properties of many nuclei, such as masses, beta-decay half-lives, Pn values and neutron-capture rates have a particularly large impact on the r-process calculations which require theoretical predictions for many nuclei too far away from stability to be measured.

In addition, it was evidenced recently that **gamma emission from neutron-unbound states** populated in the beta decay can be much larger than anticipated [13,44-46]. It was proposed [13] to use this piece of experimental information to constraint the neutron capture cross-section for very neutron-rich nuclei far from stability, which is otherwise obtained from theoretical Hauser-Feshbach (HF) estimates. **The TAGS technique thanks to its high efficiency to high energy gamma-rays is the best suited to measure accurately the gamma component of the gamma/neutron ratio in order to constrain the neutron capture rates where direct measurements are not possible yet. These studies are contemplated in the region around ^{132}Sn which is close to the r-process path, but also in the region around the doubly magic ^{78}Ni where beta-delayed multi-neutron emission has been observed [47] and gamma emission** from neutron-unbound states populated in the beta decay are expected. The region of the third r-process peak could also be investigated [48]**. The improvement in energy resolution provided by the ring of $LaBr_3$ crystals of the STARS will allow revealing the fine structure in the β-strength function in the case of decays to nuclei with very low level densities (as those occurring close to doubly-magic nuclei). These TAGS measurements will provide excellent constrains of the theoretical calculations in the regions of the chart close to the r-process path with unprecedented quality.**

- **Investigation of low-lying collective modes through β-decay**

Collective modes are predicted to appear all the more at lower energies that nuclei become neutron-richer. Collective modes are of crucial importance in nuclear structure as they reflect the ability of the nucleons to vibrate coherently and provide insights into the properties of the nuclear force. The study of collective modes puts severe constraints on theoretical models. They are also the only observables that we can study on earth providing access to the intrinsic properties of nuclear matter, entering in the modelisation of astrophysics phenomena like supernovae or neutron stars. Pygmy dipole resonances (PDR) could be the consequence of the appearance of neutron skins in medium to heavy neutron-rich nuclei. The PDR might deliver information on neutron-star properties [49]. Important information on the equation of state (EOS) of neutron-rich matter via strength-neutron-skin thickness correlation could be obtained [50].

The presence of low-lying PDR could influence on nucleosynthesis processes especially (n,γ), (γ,n) reactions playing an important role in the r-process [51].

Many questions remain about the collective modes when going more exotic. Up to now, a technical barrier has been the low intensity of the accessible exotic beams which limits the possible studies using standard nuclear or electromagnetic probes. Beta decay has the potential to constitute a new complementary probe for low-lying collective modes. Further away from stability, as the energy window opened by beta decay increases the energy of the pygmy modes decreases, allowing their excitation through the Gamow-Teller operator when the spin and parity conservation conditions are fulfilled. **Beta decay offers then new possibilities to study systematically the presence of low-lying collective modes with the existing exotic beam intensities, whenever the required conditions of spin/parity are fulfilled.** The theoretical demonstration was provided by two models [46,52]. The model of [52] predicts that other components of the collective mode are excited through β-decay than those excited by nuclear and electromagnetic reactions. In the experimental results of [46] and [52], high resolution setups with a small detection efficiency were used and the data may suffer from the Pandemonium effect. **The TAGS technique, using a highly segmented spectrometer, seems to be very well adapted to tackle this problem, especially to evidence high energy gamma-rays feeding the daughter ground state or first excited state. Thanks to the high segmentation of the STARS, γ–γ angular correlations can be studied in order to identify some of the spin/parity of the populated states. The high energy resolution combined with the detector multiplicity could allow to evidence the collectivity of the**

populated states at high energy, without relying on theoretical predictions. Here again the regions around ^{132}Sn and ^{78}Ni are especially well suited to these studies. The study of low-lying collectivity in neutron-deficient nuclei could also be proposed taking opportunity from the very competitive neutron-deficient beams that will be produced at GANIL in the near future.

- **Core-collapse Supernovae**

Another physics case is being studied in nuclear astrophysics in collaboration with researchers from GANIL (B. Bastin, A. Fantina, F. Gulminelli) with the measurement of Gamow-Teller strength with the TAGS technique for nuclei playing an important role in Supernovae explosions in order to constrain their electronic capture rates. The modelisation of Core-Collapse Supernova (CCSN) explosion is still challenging even if a lot of progress has been achieved during the last decade [53]. The knowledge of several nuclear ingredients is mandatory, among which the electron capture (EC) rates [54]. EC rates would play a role in the late stage of the stellar evolution and during the pre-bounce phase of the CCSN. The advanced TAS would provide the same advantages as already listed above in the other physics cases. Simulations have been shown [55,56] to be most sensitive to EC rates for neutron rich nuclei near N=50 and to a lesser extent close to N=82. Our colleagues from GANIL have performed simulations of the pre-bounce evolution of core-collapse supernovae investigating the effect of improved EC rates on nuclei developed in Raduta et al. [57]. They confirm earlier work and have found that the effect of different EC rates is clearly predominant with respect to the Equation of State (EoS), the nuclear mass model, or the progenitor model [58]. The important sensitivity found on EC rates translates into a variation of the electron fraction which impacts the inner core mass and the speed of the shock propagation after bounce. **Our colleagues have provided a list of relevant nuclei for which Gamow-Teller strength measurements would help constraining the nuclear models for the calculation of the EC rates. The beta strength of the lighter nuclei which are part of this list could be studied at the GANIL facility taking advantage of the detection performances of the STARS.**

- **^{44}Ti nucleosynthesis**

Properties of exotic nuclei are important in order to understand the astrophysical processes responsible of the abundance of the chemical element on earth and on the evolution of the stellar systems. On the proton rich side, several isotopes between Ca and Cu have β-p and β-α branches that need to be measured. For the same nuclei, decaying on states which have relevant spin for astrophysical reactions (radiative capture L=0 or L=1), their gamma decay should also be measured, for example with a TAS spectrometer. This topic is the object of a collaboration with F. De Oliveira, A. Benitez-Sanchez and B. Blank et al. As a matter of example, the nucleosynthesis of the key nucleus ^{44}Ti could be studied, in particular measuring the decay properties of β-p emitters to probe key reactions governing its production and destruction. ^{44}Ti production rates and characteristics are a good diagnostic to understand the core collapse supernova explosion mechanism. Most of the abundant cosmic ^{44}Ca comes from its ^{44}Ti precursor, and has been found in meteoritic data (enrichment of ^{44}Ca in type X pre-solar grains), which origin is attributed to condensation within core-collapse supernovae [59-61]. One of the radioactive nuclei observed by COMPTEL and INTEGRAL is ^{44}Ti. It has been observed in the supernova remnant called Cassiopea A by detection of its characteristic gamma rays at 1157keV [62-64]. Using known values of the distance and age of the remnant Cas A, half-life of ^{44}Ti and the γ-ray flux deduced from observations, a yield of ^{44}Ti has been derived, and is larger by a factor 2 to 10 than the predictions of the models [65-69]. The present light curve from SN1987A in the near Large Magellanic Cloud galaxy is believed to be powered by ^{44}Ti radioactivity. Unfortunately this γ-ray emission is below detection limits. The estimated yield of ^{44}Ti is similar to the one of Cas A and is larger than estimated by stellar calculations [63]. The quantities of ^{44}Ti produced are sensitive to the underlying physics. The production of ^{44}Ti occurs mainly during the alpha-rich freeze-out, in the silicon layer just outside the collapsed core, heated by the shock wave provoked by the matter falling supersonically onto the latter one. The amount of ejected ^{44}Ti depends on the location of the mass cut between the collapsing core and the expelled material and its spatial distribution directly probes the explosion asymmetries [70].

In order to explain the discrepancies between observations and predictions of the models, a better understanding of the synthesis of ^{44}Ti is necessary on the nuclear side, in parallel of the studies on the explosion mechanism of SNII. The et al. [71], through the use of a large scale nuclear reaction network, have first studied the reaction rates which influence the production and destruction of ^{44}Ti followed by G. Magkotsios et al. [72] and more recently by S.K. Subedi and co-workers [73].

A few of the key reaction rates found in these studies could be probed through the inverse reaction in a similar way to the case of the r-process with the measurement of the gamma-ray emission above the particle-emission threshold. **For instance the measurement with the proposed STARS of the beta emission properties of ^{48,46}Mn and ^{45}Cr (some of which being quite challenging in terms of $T_{1/2}$ and beam intensities) would allow to constrain the ^{47}V(p,γ), ^{45}V(p,γ) and ^{44}Ti(p,γ) reaction rates. Considering the short half-lives and the little knowledge of the nuclear structure of the daughter nuclei, the performances of the upgraded TAS would be extremely relevant in these cases.**

- **Origin of p-nuclei**

Another of the major issues in nuclear astrophysics concerns the **origin of p-nuclei, which are rare stable isotopes beyond iron, situated on the proton-rich side of the stability valley** [74]. Many astrophysical sites and nucleosynthesis processes are investigated in order to explain the observed solar abundances. Calculations are performed on nuclear reaction networks that involve around 2000 nuclei and 20000 reactions, and rely mostly on the Hauser-Feshbach statistical model. To improve the nuclear physics input, **some crucial cross sections need to be determined experimentally**. **Measurements of important proton and alpha capture reactions are planned at the SPIRAL2-NFS facility. The IP2I partners of this project have deposited a LoI on the topic** [75]. When the reaction product is a stable nucleus, in-beam techniques have to be used to measure the cross section such as **gamma summing** [76]: it consists in measuring the intensity of the sum peak whose energy corresponds to the whole gamma cascade that de-excites the produced nucleus. **The actual limitations come from the uncertainty on the sum peak efficiency. The combination of the calorimetric and spectroscopic properties of the STARS detector will allow to overcome these limitations.**

Neutrino Physics and Applications around nuclear reactors objectives

A major concern in **neutrino physics** has been the better determination of the oscillation parameter θ_{13} with large detectors placed close to nuclear power plants [77-79]. The detection of antineutrinos has also been proposed as a potential tool for reactor monitoring as the measured properties of the antineutrinos reflect the reactor fuel composition [80]. In this context, a re-evaluation of the reactor antineutrino energy spectrum [81,82] based on the conversion of integral beta energy spectra measured by [83] led to the reactor anomaly - a deficit of about 6% between the theoretical prediction and the neutrino experiments at short baselines, and the shape anomaly – a distortion of the measured energy spectra by the large reactor neutrino experiments with respect to the converted spectra in the 5 to 7 MeV antineutrino energy region [84]. Exciting new physics could arise from these anomalies such as the existence of light sterile neutrinos [85], while it could have also been triggered by an underestimation of the systematic uncertainties associated with converted spectra. **More recently, it has also been suggested that not taking into account first forbidden transitions in the antineutrino energy spectrum calculation could be responsible for large systematic uncertainties and could explain part of the observed anomalies [86,87]. Nuclear physics has clearly the possibility to help solving this particle physics puzzle which can also have an impact in astrophysics.** The antineutrino spectrum can be calculated using the information contained in nuclear decay databases of the fission products (summation method, SM) [81]. But it was shown that some data of the evaluated nuclear databases suffer from the Pandemonium effect [3]. The situation is similar to the one found in the evaluation of the reactor decay heat [88]. **The TAGS collaboration has carried out three experimental campaigns during the last decade at the JYFLTRAP of Jyväskylä (Finland) measuring a large set of data in order to improve the quality of the predictions for both antineutrino spectra and reactor decay heat [11,12,89-95]. The obtained antineutrino spectrum and flux [95] compared with the Daya Bay ones [96] show the best agreement in shape in the energy range 2 to 5 MeV and in flux obtained so far with a model. The flux deficit observed by Daya Bay with respect to the SM is now reduced down to 1.9% leaving little room for the reactor anomaly, provided that the correction of more Pandemonium data should reduce this discrepancy. The MTAS collaboration has also measured some nuclei of interest for the antineutrino spectra with the TAGS technique [97,98].**

However, the shape anomaly remains unexplained. Efforts should be focused on nuclei which data still suffer from the Pandemonium effect, contributing mostly in the energy range above 4.5 MeV and nuclei which exhibit large forbidden transitions. **These nuclei lie further from stability than the ones previously measured. The challenge to finally obtain reliable calculations of the antineutrino spectra over the full energy range will be to perform TAGS measurements on these nuclei [99,100]. This is possible if one associates the high efficiency of the existing TAS with a better energy resolution than the state of the art of the TAS. The JUNO-TAO [101] experiment aims at measuring the antineutrino spectrum near a power plant with unprecedented energy resolution, so that the fine structure of the reactor antineutrino spectra, due to the individual contributions of the FP could be evidenced. The higher energy resolution of the $LaBr_3$ crystals that will be added to the DTAS will allow to perform this "high resolution spectroscopy of antineutrino spectra" and to compare the improved SM with the JUNO-TAO results. These exciting possibilities could open a new era of nuclear data study through reactor antineutrino spectra and would undoubtedly help reactor monitoring with antineutrinos.**

As quoted above, the Pandemonium effect affects the summation calculation of another quantity of interest for reactor safety, the decay heat (DH) [102]. DH is the energy released with time by the nuclear fuel following the shut-down of the chain reaction in a reactor. It is essentially made up of radioactive (β, γ, and α radiations) decays of the fission products (FP) and actinides. On average, it represents a residual power of 6 to 12% of the nominal power of the reactor just after its shut-down. These numbers are huge and motivate the necessity to have a good knowledge of the DH for both the evaluation of the reactor safety and various economic aspects of nuclear power generation. Important discrepancies have been observed between summation calculations which used the information stored in nuclear databases taken worldwide and benchmark experiments [86,99]. An international effort started [86] and a priority list of TAGS measurements was established [99]. The specific inaddition of the most performant spectrometer proposed here would be the accurate determination of the contribution to DH of shorter lived-nuclei, not accessible to TAGS with the existing spectrometers.

How the STARS lifts the current limitations of the existing TAS

The addition of a ring of 16 2" x 2" x 4" $LaBr_3$:Ce modules between the two halves of the DTAS or combined with the Rocinante TAS will **offer the opportunity of an unprecedented combination of calorimetric and spectroscopic tools for beta decay and in-beam measurements. The large efficiency combined with the very good energy resolution and timing of the $LaBr_3$ crystals appear to be a solution to the study of more exotic nuclei with the TAGS technique, allowing to tackle the physics cases above mentioned where better energy resolution can represent an advantage**. In addition, the higher segmentation of the proposed detector will **offer the possibility to perform** γ-γ **coincidences and measure angular correlations of specific γ-ray cascades.** These new possibilities will be **very useful in the study of more exotic nuclei or cross-section measurements**. **In the latter case, the knowledge of the γ-cascade multiplicity will allow to have a good control of the uncertainty on the sum peak efficiency [76]. The** γ-n **discrimination will allow eliminating the parasitic (α,n) reactions that usually spoils the radiative α-capture measurements.** The internal contamination of $LaBr_3$ crystals is eliminated through the use of β-γ coincidences or γ-γ coincidences.

b. Proposed Instrument

Position relative to the state of the art regarding the proposed instrumentation

The development of a TAGS method efficient and systematic appeared in the 1990s [103] and has been improved since then. TAS are now segmented allowing "multiplicity" measurements and the analysis methodology has been noticeably improved [104]. The existing TAS worldwide are either made with BaF_2 detectors (Rocinante [2]), or NaI crystals (DTAS [1], MTAS [105], SUN [106], *Lucrecia* [107]). They all exhibit a limited energy resolution, the best one being reached with the NaI spectrometers (MTAS, DTAS, *Lucrecia* and SUN). SUN has a limited segmentation and lower efficiency with respect to DTAS and MTAS, MTAS being the most efficient. The IFIC group members have been the leaders of three TAS developments: *Lucrecia* (a large NaI monocrystal installed permanently at ISOLDE

CERN), *Rocinante* (made of 12 BaF_2 crystals offering a detection efficiency of gamma-ray cascade larger than 80%) and lately the DTAS (a 18-fold segmented NaI(Tl) spectrometer with rectangular crystals of 15x15x25cm^3, with an excellent efficiency of 80-90% to detect a single γ-ray associated with an individual crystal energy resolution of 7-8%). Papers showing a very good control of the response of these spectrometers have been published in peer review journals [104, 108]. They have coupled these spectrometers to several types of β detectors: silicon and plastic detectors and they have coupled the DTAS to the AIDA segmented silicon detector designed for β-decay stydies at in-flight facilities [109]. The teams involved in this project have performed together so far three experimental campaigns with two detectors built by the Valencia and Surrey groups at the IGISOL facility in Jyväskylä [110]. Rocinante was used in 2009 and coupled with a silicon detector for beta-gamma coincidences to reduce the background contribution. During the second campaign in 2014, the DTAS was commissioned and coupled with a plastic detector for beta-gamma coincidences. The third campaign was held in Jyväskylä in September 2022 with the detector Rocinante and a plastic beta detector coupled to the digital DAQ FASTER [111].

To obtain the beta intensity distribution from a TAGS measurement, the TAGS inverse problem has to be solved, which consists in extracting the real beta feeding from the data provided that it is deformed by the detector response [104]. There are different ways to extract this beta feeding distribution. **The analysis procedure that we follow for a decade has been developed by the partners of this project from IFIC and CIEMAT**. In [104] several algorithms were explored. From those that are possible, the expectation maximization (EM) algorithm is conventionally used, since it provides only positive solutions for the feeding distributions and no additional regularization parameters (or assumptions) are required to solve the TAS inverse problem. **This expertise places the teams involved in this project among the world-experts of the TAGS technique and of the associated spectrometers.**

The (NA)^{2}STARS project proposes for the first time the combination of two types of crystals, either the NaI crystals of the DTAS which exhibits overall good characteristics (ρ=3.67 g/cm^3, Zave=31.5, τ_{decay}=230 ns, energy resolution ~7 %@662 keV) for a moderate cost or the 12 BaF_2 crystals from the Rocinante TAS which have a worse energy resolution but are fast crystals and less sensitive to neutrons, **with 16 $LaBr_3$:Ce crystals** (ρ=5.08 g/cm^3, Zave=40.5, τ_{decay}=17 ns, energy resolution ~3 %@662 keV) which excel in energy resolution but which are ten times more expensive, **to make a new TAS. This device will be the first TAS to combine an unprecedented segmentation with very high efficiency, very good energy resolution and fast timing through its $LaBr_3$ ring, making of this tool the world-leading TAS spectrometer to tackle the physics cases listed in the first section of this document.**

A potential disadvantage of $LaBr_3$:Ce is the large intrinsic background associated with the decay of unstable ^{138}La ($T_{1/2}=10^{11}$ y, ~1 Bq/cm^3), a contribution which will be effectively suppressed in our measurements as **the TAGS data are tagged with a β-decay signal.**

The design of the 2” x 2” x 4” LaBr3:Ce individual modules has been performed by the IFIC-Valencia and Ciemat-Madrid teams, members of the DESPEC collaboration in the frame of the design studies [112] leading to the existing spectrometer DTAS. This detector was designed to be employed in the determination of β-decay intensity distributions of exotic nuclear species at the focal plane of the NUSTAR Super-FRS. In the frame of this project [112], individual modules for two options (NaI vs $LaBr_3$) were designed and characterized through both simulation and experimental tests. The NaI option was selected to build the full spectrometer because of the high cost of $LaBr_3$ crystals, leading to the DTAS which is one of the most performant TAS in the world, but at the price of losing the precious better energy resolution, fast timing and segmentation of the $LaBr_3$ option. It is now timely to make an advanced TAS that would offer these skills.

Characteristics of the proposed instrumentation

The designed $LaBr_3$ crystal has a cross-section of 5.1cm times 5.1cm which fits a standard 2 inches square PMT, taking into account the inter-crystal spacing due to dead material. The minimization of dead materials was investigated together with the sole provider of this type of crystal at that time: Saint Gobain. **The key of the applicability of the TAGS technique is the very good control of the response of the detectors, that is why it is mandatory to know precisely what are the thicknesses of the**

constituting materials. Fig. 6 shows a picture of one LaBr3 crystal and Fig. 7 shows an example of the excellent agreement found between the Monte Carlo simulation of one $LaBr_3$ crystal prototype and measurements with a source of ^{60}Co [113].

Several photomultiplier tubes (PMT) were tested and the selected one was the R6231 from Hammamatsu, a 2 inches diameter PMT with enhanced quantum efficiency and low gain. **The energy resolution of the detector prototype was found to be twice better than the NaI crystal (3.1% at 1.33MeV) with a smaller light yield non-proportionality.**

Fig. 6: photo d'un des modules de $LaBr_3$ de (NA)^{2}STARS.

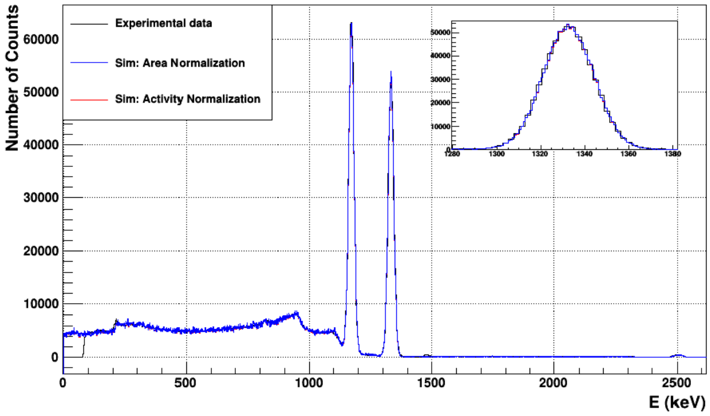

Fig. 7: Comparison of experimental and Monte Carlo simulated spectra recorded with one $LaBr_3$ detector. The black line is the experimental data, the blue line is the spectrum simulated with GEANT4, normalized to the total number of counts in the experimental spectrum and the red line is the spectrum simulated with GEANT4, normalized to the source activity (3% uncertainty) [113].

Delayed neutrons are a source of additional background since the neutrons (with energies from tens of keV to a few MeV) can interact with the detector material producing γ-rays through radiative capture and inelastic scattering. This effect has been studied by our partners using GEANT4 Monte Carlo (MC) simulations and experimentally by the partner teams [114,115]. More recently, our IFIC partners have investigated the possibility to use the neutron sensitivity of the DTAS to extract the beta-delayed neutron fraction (Pn) from the data. It was concluded that the absolute measurement of the Pn is not possible with the existing TAS. **The only possible way to discriminate against the neutron signals is through timing, using the fact that β-delayed neutrons travel more slowly than γ-rays. Therefore the timing properties of the $LaBr_3$ crystals are specially adapted to tackle the gamma/neutron discrimination and to combine the gamma and neutron measurements at once. No existing TAS worldwide have such possibilities.**

Provided the high neutron sensitivity of the existing TAS and the large Pn values of some of the nuclei of interest, the development of reliable GEANT4 simulations of the TAS responses to neutrons is mandatory. In the current version of GEANT4 the existing internal database is incomplete and sometimes inconsistent [115]. **Our CIEMAT partner [116] has developed a tool which allows the inclusion in GEANT4 of complete standard databases to perform the simulations. Furthermore, the GEANT4 γ-ray cascade generator called after neutron capture was also modified in order to obtain realistic cascade energy and multiplicity distributions.** The new algorithm is currently used in the TAGS data analysis performed by the teams involved in this project.

The timing resolution of the LaBr$_3$:Ce prototype predicted by the MC simulation of the module is 0.29 ns. We expect to obtain a similar result experimentally thanks to the use of the recent digital modular acquisition system developed at the Laboratoire de Physique Corpusculaire in Caen France, FASTER [111]. The Subatech team has acquired some expertize with the FASTER electronics and DACQ through the E-Shape project (collaboration Subatech – Valencia - Surrey) aiming at the measurement of the electron energy spectra for forbidden non-unique β-decay transitions (of interest for reactor antineutrinos [117] and nuclear structure and astrophysics). In the frame of E-Shape, the Subatech team has been responsible for the design and construction of the mechanics and electronics of two telescopes each made of a silicon and a thick plastic detectors. The detectors have been commissioned successfully in May 2019 in Jyväskylä. The experiment was initially planned in May 2020 but has been delayed due to the COVID-19 issue. In 2022 the E-Shape experiment could be performed in Jyväskylä in January successfully, and a new TAGS campaign delayed by the sanitary crisis could be performed in September as well. In this campaign, the Subatech team has been in charge of the DACQ of the Rocinante TAS that we have developed with FASTER. The experiment worked also successfully.

FASTER is a triggerless system develop to fulfil the need of nuclear experiment. The readout board is composed of a motherboard which can hold two types of daughter board: CARAS and MOSAHR boards. Both boards are equipped with a FPGA device in which a Measurement Numerical Module is programmed: QDC-TDC and Trapezoidal spectrometer are the ones that we are usually used. CARAS provides users a dual channel 12-bits up to 500 Msps ADC capability while MOSAHR provides a four channel 14-bits up to 125 Msps ADC capability, ideally suited for high resolution energy measurement. Even if the CARAS clock is 2ns, the TOF measurement can have a time resolution down to 7,8 ps using an interpolation calculation.

Design studies of the STARS setup based on the DTAS have been started by the Subatech group with the GEANT4 code [118]. Fig.8 shows two configurations under study, the geometry in Fig. 8 a) optimizes efficiency but not the neutron/γ discrimination, Fig. 8 b) is a compromise between efficiency and neutron/gamma-rays discrimination by time of flight.

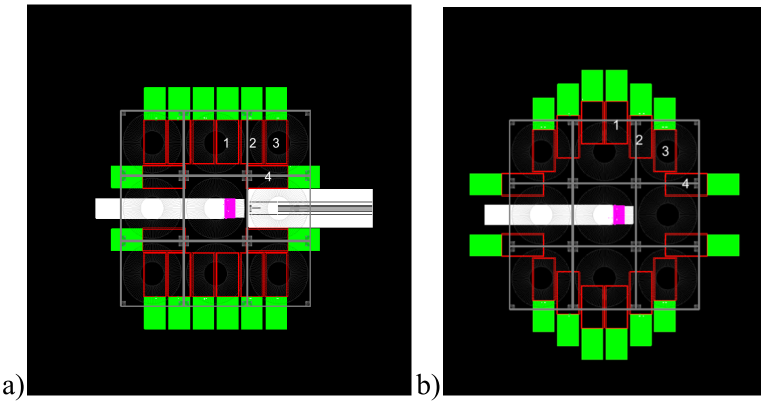

Fig. 8: view of possible arrangements of the 16 LaBr3:Ce (red) in the middle of the NaI crystals (grey) with a central hole to accommodate the beam tube, the beta detector (pink) and a germanium detector in the configuration of the JYFL facility.

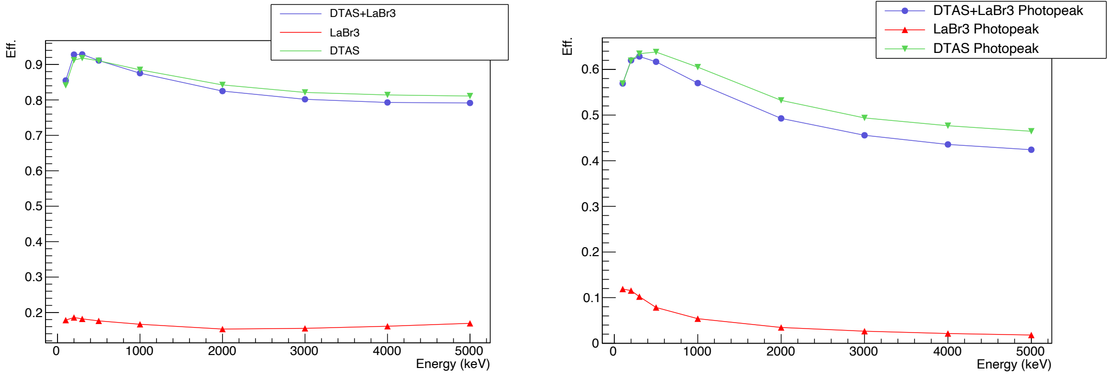

Fig. 9: Total (left) and photopeak (right) efficiencies of the STARS configuration of Fig.8 b) in the middle of the DTAS [118].

In the latter configuration, the total and photopeak efficiencies of the STARS are displayed in Fig. 9. The fast timing of the $LaBr_3$ modules could allow the discrimination of β-delayed neutrons from gamma-rays for neutron energies up to at least 3 MeV even in the compact geometry of Fig. 8 a) (and maybe more with sub-ns resolution), with times of flight of 27ns for neutrons at 100 keV and 5 ns at 3 MeV (4 ns at 5 MeV) in the closest module to the implantation point. Slightly less compact configurations are under study and the experimental tests of the modules and the design studies of the first months of this project will allow to choose a final geometry. The mechanical design could allow several geometrical possibilities with the same mechanical support. Neutrons which would have interacted first in a NaI crystal before interacting in a $LaBr_3$ have also to be taken into account.

The combination of the two sets of crystals could consist in selecting well-defined γ-rays in the high resolution $LaBr_3$ detectors and studying the other γ-rays detected in the NaI crystals to study closely the properties of γ-cascades. Γ–γ correlations could be performed. They will require large statistics in the $LaBr_3$ crystals. Thanks to the γ/n discrimination through TOF in the $LaBr_3$, neutrons could be selected and γ-rays from the daughter nucleus in the same event could be measured in the NaI crystals. A specific care will be devoted to the determination of the efficiency of each subpart of the STARS.
$(NA)^2$STARS will offer the possibility to perform γ-γ coincidences in favorable cases. A first study performed with the GEANT4 code has shown that it would be possible to measure angular correlations of specific γ-ray cascades (see talk given at the technical ISOL-France meeting in Nov. 2021). In addition, the segmentation of the STARS will be essential for the in-beam determination of cross-sections the measurement of level densities with the “beta-Oslo” method [119].

The design studies mentioned above have been started first for the upgrade of the DTAS, but the design studies for the upgrade of Rocinante will start in 2023 (see the PBS provided in annexe of this document). Upgrading both TAS with the same 16 $LaBr_3$ will offer more flexibility and availability of the detectors for the foreseen experiments. The choice of one TAS or another to combine with the $LaBr_3$ will depend on the required characteristics (efficiency, energy resolution, timing properties).

II - Organisation and implementation of the project

a. Foreseen Experiments @ the GANIL facility

The future GANIL facility and especially the DESIR hall will be one of the best places worldwide (beam-intensity and beam-quality -wise) to study the physics cases presented above on neutron-deficient nuclei (^{100}Sn region, A~80 for rp-process, ^{44}Ti nucleosynthesis). The time frame to benefit from these future beams and installation is at the horizon 2027. The possibility to install a TAS at the S3-LEB facility (before the availability of DESIR) has not been planned before and thus deserves to be studied in more details, depending on the start-up of DESIR. Discussions have started with our GANIL collaborators [120]. Another possibility would be to use the fusion-evaporation source currently under development if the proof of principle is validated.
Before 2027, some of the physics cases above could be performed with beams produced by fragmentation and sent in the LISE spectrometer, including some neutron-rich nuclei even if it would be more difficult. As mentioned above, our IFIC partners have performed TAGS experiments at fragmentation facilities (GSI and Riken), using a DSSSD detector (AIDA). Collaborators from GANIL and Bordeaux have already performed beta decay experiments at LISE with implantation detectors, so that a TAGS experiment at LISE with an implantation detector should be possible. Another possibility explored by our GANIL collaborators has been to implant a purified beam in a thick tapestation. This possibility could be explored as well for some of the physics cases of interest and would allow to perform a TAGS experiment at LISE at a rather short time scale. The selection of the cases for which LISE would offer good beam conditions for TAGS experiments is under investigation in collaboration with GANIL colleagues, as well as the required optimal setup [120].
In addition to TAGS experiments with the STARS, the 16 $LaBr_3$ modules could be used to complement other detection setups used in GANIL. As an example, in Autumn 2022, two $LaBr_3$ modules were added to the FASLTAFF experiment at NFS as a first test. We foresee to add more modules to the next

FALSTAFF campaign next year in order to have access to information about prompt gamma-rays from the fission processes.

b. Project management

A management and scientific board will be created by the collaboration including one representative of each partner. It will have the responsibility to manage the technical part of the project as well as the physics program and the institutional relations.

Discussions with the physicists and engineers from GANIL will be necessary along the project to make possible the installation of the STARS on the GANIL beam lines. Discussions with physicists have started already around the possible experiments that could be carried out at the LISE facility first and at the S3-LEB and/or DESIR facilities at the horizon 2027, in order to determine the required developments, or be informed about the on-going developments at GANIL which may facilitate our experiments.

The management of the technical part of the project will follow the basic rule of project management by creating the documents to help the organization and the follow up of the project:

- PBS (Product Breakdown Structure) which describes the structure of the project ;
- WBS (Work Breakdown Structure) which describes the work to be done to obtain readiness of the detector and the repartition of the tasks among the partners ;
- Planning to estimate the time needed to have the detectors ready ;

These documents are readable in annexe to this document.

Development Plan

The goal of the technical part of $(NA)^2$STARS is to perform an upgrade of both existing spectrometers DTAS and *Rocinante*.

The upgrade of both DTAS and *Rocinante* integrates a ring of 16 $Labr_3$. The systematic characterization of each $LaBr_3$ module has to be performed (with sources and Geant4 simulations).

A new design of spectrometer has to be done with a new mechanical structure and a new shielding in each case. In the case of the upgrade of Rocinante, a new mechanical structure will be designed to obtain more modularity and the refurbishing of the 12 BaF_2 is required. This is why it occurs later in the planning in annexe to this document. This will be performed by Scionix, under the responsibility of the IFIC of Valencia.

Those spectrometers will be used at the GANIL facility at the S3-LEB/DESIR and LISE beam lines. Therefore, a common development for the two detectors has to be done:

- Two support tables, adjustable in X,Y and Z, compatible with the two beam lines or with the two spectrometers.
- Two versions of the beam tube:
    - An adaptation of the existing one in the case of S3-LEB/DESIR with the use of a tape ;
    - A complete new design in the case of LISE with the use of the AIDA tracker developed by the Spanish team or a double sided silicon strip detector lent by GANIL.

The timing of those upgrades will be as follows (see planning in annexe):

- Design of the support table compatible with the Ganil beam lines and taking in account the upgrades of DTAS and Rocinante
- Design of the beam tubes compatible with LISE in 2023
- Design of the beam tubes compatible with DESIR in 2026
- Modification of the shielding for the DTAS upgrade
- DTAS foreseen to be operational in 2024 at LISE beam line

- DTAS foreseen to be operational in 2026 at DESIR beam line
- Reconditioning of BaF_2 crystals in 2023-2024 by Scionix
- *Rocinante* foreseen to be operational in 2025 at LISE beam line
- *Rocinante* foreseen to be operational in 2026 at DESIR beam line

Risk identification

Several risks have been identified which may affect the good progress of the project:

- Delay in the readiness of the beam line
- Delay or lack of funding
- Increase of the cost or delivering delay of the $LaBr_3$
- Integration of DSSD in the beam tube for LISE beam line (mechanicaly and electonicaly)
- Specific safety rules at GANIL

To minimise the two last risks, some technical discussion with the GANIL is expected as well as a design review for both spectrometer before the installation.

c. Scientific coordinator and its consortium / its team

The scientific coordinator of the project is Muriel Fallot (Subatech). She is coordinator for several projects in France and the leader of the Nuclear Structure and Energy (SEN) group. M. Fallot is co-spokesperson of several TAGS experiments motivated by neutrino physics and the study of pygmy modes. She will devote 50% of her research time to the project. **The members of the SEN team of Subatech are** A. Beloeuvre (PhD student), E. Bonnet, M. Estienne, M. Fallot, J. Pépin (PhD student) and A. Porta who are involved in this project and L. Giot and Y. Molla (PhD) who develop reactor simulations and participate to the TAGS campaigns. The SEN team has used the TAGS technique for the last decade [20,69] in close collaboration with the IFIC of Valencia. The group has a leadership in the analysis and estimate of impact of the TAGS measurements on antineutrino spectra using simulations, with excellent visibility as shown by [89,90,95,99,100]. The group has designed, built and operated the muon veto detector of Nucifer [121] and has designed with the IFIC and the University of Surrey an electron detector (E-Shape) with its vacuum chamber and its DAQ [111]. They have acquired 2 $LaBr_3$ modules and recently prepared the FASTER DAQ for the TAS *Rocinante* for the latest TAGS campaign at the facility of Jyväskylä. During his PhD, A. Beloeuvre has performed simulations of the performances of the STARS built with the DTAS and a ring of 16 $LaBr_3$ detectors, based on the GEANT4 simulations developed initially by Ciemat ($LaBr_3$) and the DTAS (IFIC). The $(NA)^2$STARS project benefits from the strong support of the technical services of Subatech, with the involvement of S. Bouvier (IR) as technical responsible of the project, at a level from 40 to 80% FTE depending on the years, and A. Cadiou who is responsible for the mechanical developments of the project. In addition, the project will involve 2 technicians for the mechanics and electronics at Subatech.

The team of IP2I Lyon (A. Chalil (postdoc), C. Ducoin, O. Stezowski) has expertise (with responsibilities in European collaborations such as AGATA[122], PARIS[123]) in γ-ray detections (semi-conductors, scintillators) from simulations at the lowest level (signal generation, GEANT4) and along the whole data processing chain and are co-spokespersons of the Letter of Intent to SPIRAL2-NFS related to the p-process. They have supervised a Master 2 internship (4 months, J. Pépin) to perform simulations of the STARS with the DTAS with the GEANT4 software in 2022, starting from A. Beloeuvre's work. They will be in charge of the study of the design of the STARS with GEANT4 for in beam cross-section measurements at NFS and the required installation (see reference [75]). A participation of the IP2I mechanical workshop is contemplated.

The IFIC team of Valencia (J.-L. Taìn, A. Algora, E. Nacher and B. Rubio) is composed of the experts of the TAGS technique in Europe. They have co-designed and built the *Lucrecia* detector at ISOLDE (CERN), the *Rocinante* detector (with the University of Surrey) and lately the DTAS detector in the frame of the FAIR project and the BELEN neutron detector. They have also developed a robust analysis methodology [2] based on the Bayes theorem. They have proposed the TAGS measurements for the study of γ-n competition above the neutron emission threshold [3,13], for the reactor decay heat [25] and are the authors of the TAGS results obtained on neutron-deficient nuclei [3,9]. They have acquired one $LaBr_3$ module. They will be responsible for the maintainance of the NaI modules from the DTAS and the BaF_2 modules from *Rocinante*. They will take care of the refurbishment of *Rocinante* as well. IFIC will participate actively to each step of the project.

The team of CIEMAT Madrid (D. Cano-Ott) has expertise in TAGS experiments and contributed to the development of the analysis methodology [2]. They have expertise in nuclear instrumentation, in gamma spectroscopy and in neutron detection. They have co-developed and built the MONSTER neutron detector and have acquired 4 $LaBr_3$ modules. They have developed tools for the GEANT4 software allowing to simulate more accurately the neutron interactions with matter. They will be in charge of the maintenance of the 4 $LaBr_3$ modules and participate to the characterization of the full detector response with the GEANT4 software.

d. Implemented and requested resources to reach the objectives

The list of requested resources is the following:

- 18 LaBr3 (16 + 2 spares) : 18 * 34000
- 40 channels CARAS (10 CARAS boards + 1 spare) : 11*4500
- 36 channels MOSAHR (5 MOSAHR boards) : 5*4500
- 1 FASTER crate 5000€
- HV Crate from CAEN + 3 HV boards 12 channels + 1 LV board 12 channels (20000€)
- Cables and connectors 2k€
- Mechanical supports : 120k€
- NIM modules: 1 * NIM/TTL/NIM converter 1200€, logic and analogic FIFOs : 4000€
- DAQ Computer 1800€
- Hard drives for experiments (2000€)

To which the cost of mechanics, transportation and travels should be added. The number of electronic channels includes signals from the DTAS or Rocinante and the ones from the LaBr3 modules, and also from one beta detector, an additional Germanium detector used to control the purity of the beam, signals from a tapestation (when requested), and a pulser signal.
Note that we already have a TAS repository at the in2p3 Computer Center where experimental data and analysis codes are stored by the collaboration.

In total, the cost of the project is 976,8k€ for 5 years, without manpower, including the detector modules, electronics, mechanics, transportation and travels. Some of these resources have been already implemented by the partners of the project:
Equipment:

- In 2020 and before: 6 $LaBr_3$ modules (Ciemat: 4, IFIC: 1, Subatech: 1).
  Electronics (Subatech): FASTER: 3 CARAS boards (12 channels) (3*4 4500€), 1 FASTER crate, 1 MOSAHR board (8 channels, 4500€), 1 NIM module (TTL/NIM/TTL converter) 1200€, 1 Logic and 1 analogic FIFO (2*2000€)
- In 2021 (Subatech): 1 $LaBr_3$ and the HV supply: crate and 3 HV (3*12 channels) and 1 LV boards (1*12 channel)
- In 2022 (Subatech): 1 computer (1800€) and a part of the cables and connectors (1500€)

In total, already 262,8 k€ have been invested in the project by the partners up to now (not including manpower).
714k€ remain to be funded from 2023 to 2027 to reach the objectives.

Example of funding timeline for the acquisition of the remaining requested resources:

- In 2023:
  - 5 LaBr3 modules (quote at 34000€ one module in 2022 by Saint Gobain) ;
  - 3 CARAS and 2 MOSAHR boards (FASTER);

    - The mechanical design associated to the installation of the STARS at GANIL on the LISE or S3-LEB/DESIR facilities will start and some equipment should be purchased (see the PBS, beam tube, table, vacuum equipment…) ;
    - Some travel expanses for the collaboration (meetings for the design of the STARS, for the preparation of the implantation in GANIL, etc.)
- In 2024:
    - 4 LaBr3 modules (assuming 34000€ each module) ;
    - 3 CARAS and 2 MOSAHR boards ;
    - The mechanical design associated to the support of the STARS and to the installation at GANIL on the LISE or S3-LEB/DESIR facilities will be on-going and some equipment should be purchased (see the PBS, beam tube, table, vacuum equipment…) ;
    - Some travel expanses for the collaboration (meetings for the design of the STARS, for the preparation of the implantation in GANIL, etc.)
- In 2025:
    - 2 LaBr3 modules (assuming 34000€ each module) ;
    - 2 CARAS boards ;
    - The mechanical design associated to the support of the STARS (with *Rocinante*) and to the installation at GANIL on the LISE or S3-LEB/DESIR or NFS (for cross-section measurements) facilities will be on-going and some equipment should be purchased (see the PBS, beam tube, table, vacuum equipment…) ;
- In 2026: some mechanical adaptation to the S3-LEB and / or DESIR facilities will be necessary.
- In 2027: some mechanical adaptation to the S3-LEB and / or DESIR facilities will be necessary.

In addition to this list, some funding is requested for the transportation of the equipments from one laboratory to another and eventually to GANIL for the experiments (see table 1 below). 6000€ per year are requested for meetings among the partners along the project and 20000€ when experiments will occur (funding for 10 people from Subatech and IP2I for 2 weeks).

Note that the granularity of the STARS offers a great flexibility in the funding timeline depending on the possibilities in the next years. The required number of crystals to reach 16 could be purchased in three thrids from 2023 to 2025 (and the two spares in 2026), which would smooth the expanses over the years. This would imply that the first experiment in 2025 for instance at the LISE facility would maybe not include the full ring of 16 crystals. The performances of the STARS would be less optimal but still valuable as an intermediate step in the project. Various intermediate configurations could be imagined, which would already constitute intermediate upgrades of the existing TAS. In this respect, one could even imagine an equirepartition of the needed remaining amount over 5 years (about 150k€ per year), which would not be the best timeline but would still allow to reach the objectives.

The possible funding partners of the project are mainly three: the GANIL facility, the CNRS/in2p3 and the Nantes University (with the NEXT project).
Nantes University would fund mainly manpower associated to the project, for instance a postdoc for 5 years and one or two PhD students with some environment. The GANIL and CNRS/in2p3 would thus have to share the main cost of equipment, transportation of the equipment and travels. The discussion with the Nantes University partner is conditioned by an agreement to fund partly the project by the GANIL and the CNRS/in2p3.
Note that a Memorandum of Understanding is in preparation by the partners of this project.

	<=2020	2021	2022	2023	2024	2025	2026	2027	Total
Equipment	208	51,5	3,3	222,5	188,5	107	20	10	810,8
LaBr3 modules	180	31,5	0	170	136	68			585,5
Electronics	28	20	3,3	22,5	22,5	9			105,3
Mechanics				30	30	30	20	10	120
Other				8	8	20	20	20	76
material transportation				5	5	15	15	15	55
miscellanous				3	3	3	3	3	15
data storage						2	2	2	6
Travels for collaboration + experiments				6	6	26	26	26	90
meetings				6	6	6	6	6	30
experiments						20	20	20	60
Manpower (non permanent)									
Postdoc :1 for 5 yrs or 2 (3+2 yrs)				x	x	x	x	x	
PhD(s) (at least 1)					x	x	x	x	
Total (all sources without manpower)	208	51,5	3,3	236,5	202,5	153	66	56	976,8

Table 1: Total cost of the project and possible timeline of the funding of the project.

e. References related to the project

The publications to which the partners have contributed are in bold character.

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ANNEXES

Work Breakdown Structure

(NA)2STAR Work Breakdown Structure

Last update: 16/11/2022 (S.Bouvier)

			Collaboration Institutes				
WBS Number	WBS Name	Responsible-Institute	Ciemat	IFIC	IP2I	Subatech	GANIL
0	**(NA)2STAR Management**						
0.1	Physics program and institutional relations	management board	x	x	x	x	
0.2	Technical coordination and interfaces	Subatech		x	x	x	x
0.3	Finances	Subatech	x	x	x	x	
0.4	Planning and breakdown structure follow-up	Subatech				x	
0.5	Product assurance, Product Database, Documentation	Subatech				x	
1	Detector module						
1.1	NaI : control, upgrade and calibration	IFIC		x			
1.2	LaBr3 : purchase, control and calibration	Subatech	x	x		x	
1.3	BaF2 : control, upgrade and calibration	IFIC		x			
1.4	Implantation detector : design, purchase, assembly and test	Subatech - IFIC		x		x	x
1.5	Documentation : storage of the detector modules status and calibration results	Subatech					
2	DTAS						
2.1	Geant4 simulation	Subatech for TAGS and IP2I for inbeam cross-section meas.	x	x	x	x	
2.2	Interface with Ganil	Subatech - IP2I			x	x	x
2.3	Detection structure : design, fabrication	Subatech	x	x	x	x	
2.4	Shielding : design, fabrication	Subatech		x	x	x	
2.5	Beam tube : design, fabrication	Subatech		x	x	x	x
2.6	Support table : design& fabrication	Subatech		x	x	x	
2.7	Documentation : storage of the design in the database	Subatech				x	
2.8	Assembly	Subatech		x		x	
2.9	Test with electonics and DAQ	Subatech		x		x	
2.10	Design reveiw	Ganil	x	x	x	x	x
3	Rocinante						
3.1	Geant4 simulation	IFIC	x	x	x	x	
3.2	Interface with Ganil	Subatech		x	x	x	x
3.3	Detection structure : design, fabrication	Subatech	x	x	x	x	
3.4	Shielding : design, fabrication	Subatech		x	x	x	
3.5	Beam tube : design, fabrication	Subatech		x	x	x	x
3.6	Support table : design& fabrication	Subatech		x	x	x	
3.7	Documentation : storage of the design in the database	Subatech				x	
3.8	Assembly	Subatech		x		x	
3.9	Test with electonics and DAQ	IFIC		x		x	
3.10	Design reveiw	Ganil	x	x	x	x	x
4	Detector Power Supply						
4.1	Low voltage power supply : design, configuration, control software	Subatech		x	x	x	
4.2	High voltage power supply: design, configuration, control software	Subatech		x	x	x	
5	Readout electronics and DAQ system						
5.1	Spectroscopy amplifier : configuration & purchase	IFIC		x		x	
5.2	Faster : hardware, software configuration & purchase	Subatech				x	
5.3	Gasifics : hardware and software configuration	IFIC		x			
5.4	DAQ for implantation detector: hardware and software design	IFIC or subatech depending on the detector		x		x	
5.5	Coupling system : design and realisation	Subatech		x		x	
5.6	Interface modules with Ganil beam system : design and realisation	Subatech		x	x	x	
5.7	Câbles and connectors : configuration & purchase	Subatech		x		x	
6	Vaccum equipment						
6.1	Primary and turbomolecular pump : purchase or borrowing	IFIC		x			x
7	Simulation and data reconstruction						
7.1	Geant4 DTAS_1 simulation	IFIC or Subatech	x	x		x	
7.2	Geant4 DTAS_2 simulation	Subatech	x	x	x	x	
7.3	Geant4 Rocinante simulation	IFIC					
7.4	Data analysis	Subatech or IFIC or IP2I depending on the experiment	x	x	x	x	
7.5	software documentation and storage	Subatech				x	
8	Transportation						
8.1	Transport box for DTAS : design & purchase	Subatech				x	
8.2	Transport box forRocinante : design & purchase	IFIC		x			

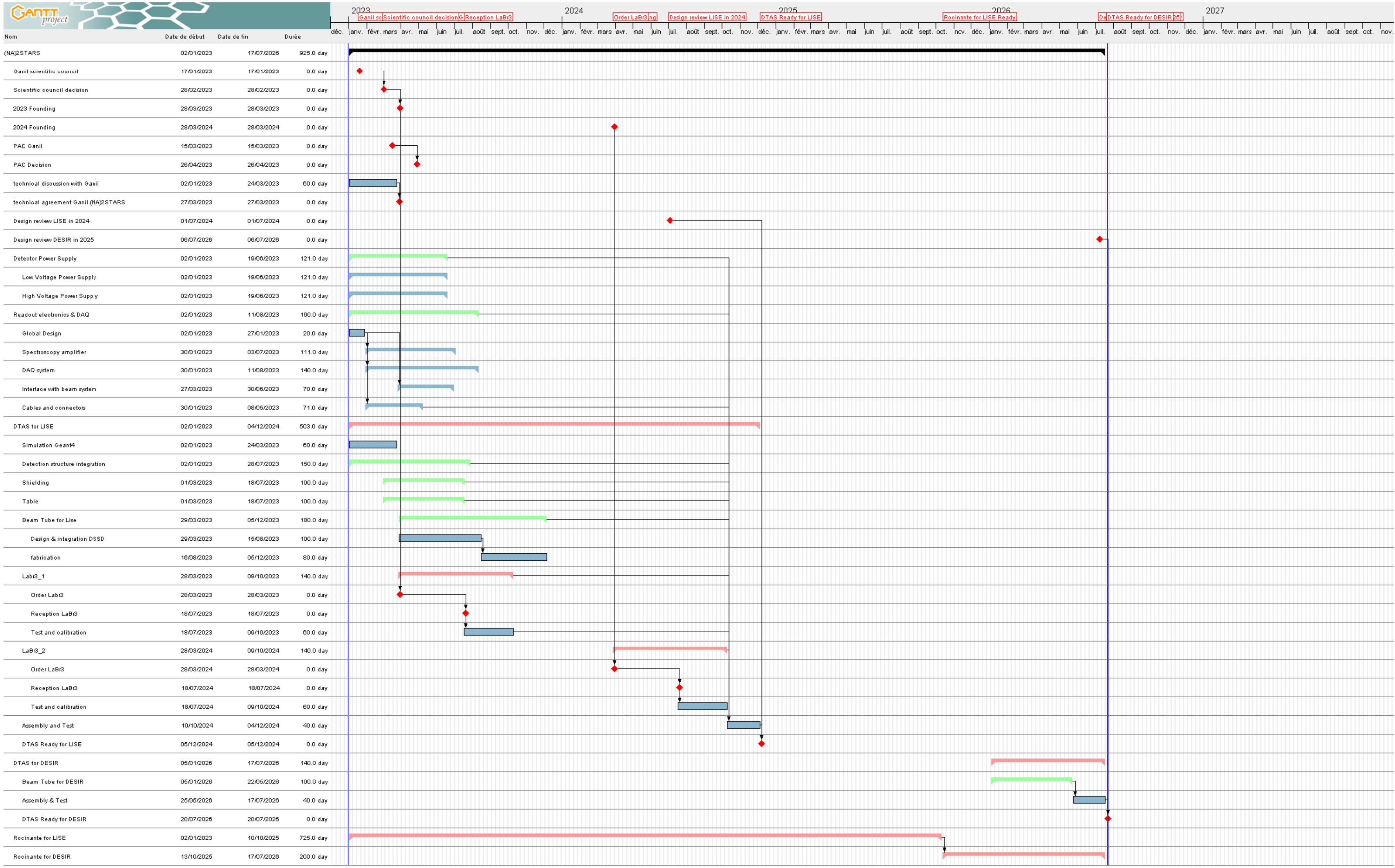
Product Breakdown Structure

(NA)2STAR Product Breakdown Structure

Last update: 12/12/2022 (S.Bouvier)

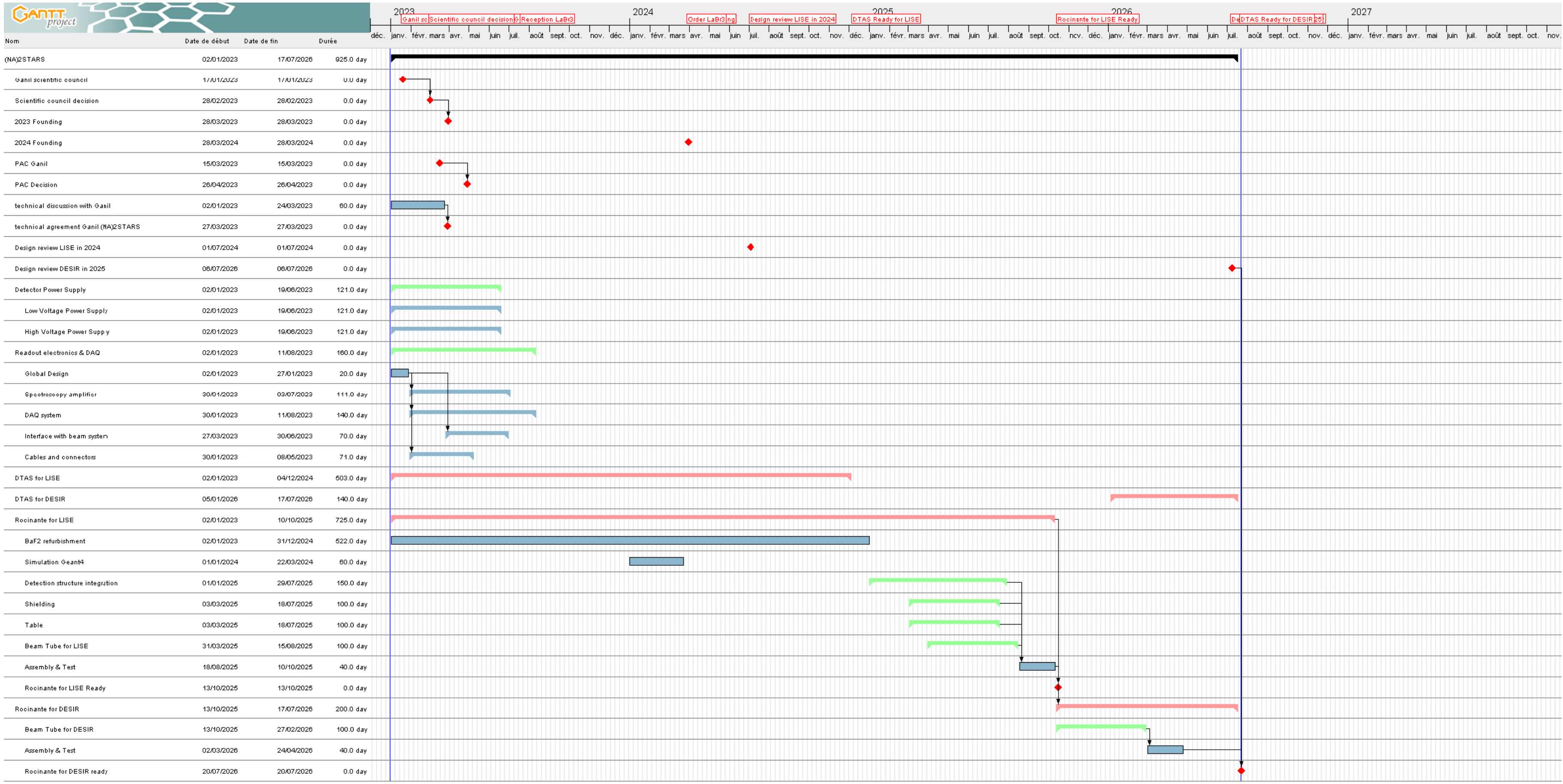
PBS Number						PBS item	Corresponding WP
1	2	3	4	5	6		
0	0	0	0	0	0	**(NA)2STAR Management**	**WP0**
	1	0	0	0	0	**Documentation**	**WP0**
		1	0	0	0	MOU	**WP0**
		2	0	0	0	Project organisation	**WP0**
	2	0	0	0	0	**Production data base**	**WP0**
		1	0	0	0	DB server	**WP0**
		2	0	0	0	DB user interface	**WP0**
1	0	0	0	0	0	**Detector module**	**WP1**
	1	0	0	0	0	**NaI**	**WP1**
	2	0	0	0	0	**LaBr3**	**WP1**
	3	0	0	0	0	**BaF2**	**WP1**
	4	0	0	0	0	**Ancillary detector**	**WP1**
	5	0	0	0	0	**Implantation detector**	**WP1**
	6	0	0	0	0	**Product assurance**	**WP1**
	7	0	0	0	0	**Documentation**	**WP1**
2	0	0	0	0	0	**DTAS**	**WP2**
	1	0	0	0	0	**Mechanical structure**	**WP2**
		1	0	0	0	**Detection structure**	**WP2**
		2	0	0	0	**Shielding**	**WP2**
		3	0	0	0	**Beam tube**	**WP2**
			1	0	0	Beam tube for LISE	**WP2**
			2	0	0	Beam tube for DESIR	**WP2**
		4	0	0	0	**Support table**	**WP3**
	4	0	0	0	0	**Equipment**	**WP2**
	5	0	0	0	0	**Documentation**	**WP2**
3	0	0	0	0	0	**Rocinante**	**WP3**
	1	0	0	0	0	**Mechanical structure**	**WP3**
		1	0	0	0	**Detection structure**	**WP3**
		2	0	0	0	**Shielding**	**WP3**
		3	0	0	0	**Beam tube**	**WP3**
			1	0	0	Beam tube for LISE	**WP3**
			2	0	0	Beam tube for DESIR	**WP3**
		4	0	0	0	**Support table**	**WP3**
	4	0	0	0	0	**Equipment**	**WP3**
	5	0	0	0	0	**Documentation**	**WP3**
4	0	0	0	0	0	**Detector Power Supply**	**WP4**
	1	0	0	0	0	**Low voltage power supply**	**WP4**
	2	0	0	0	0	**High voltage power supply**	**WP4**
5	0	0	0	0	0	**Readout electronics and DAQ system**	**WP5**
	1	0	0	0	0	**Spectroscopy amplifier**	**WP5**
	2	0	0	0	0	**Faster**	**WP5**
	3	0	0	0	0	**Gasifics**	**WP5**
	4	0	0	0	0	**DAQ system for the implantation detector**	**WP5**
	5	0	0	0	0	**Coupling system**	**WP5**
	6	0	0	0	0	**Interface modules with beam system**	**WP5**
	7	0	0	0	0	**Câbles and connectors**	**WP5**
6	0	0	0	0	0	**Vaccum equipment**	**WP6**
	1	0	0	0	0	**primary pump**	**WP6**
	2	0	0	0	0	**turbomolecular pump**	**WP6**
	3	0	0	0	0	**connection equipment**	**WP6**
8	0	0	0	0	0	**Simulation and data reconstruction**	**WP7**
	1	0	0	0	0	**Detector simulation**	**WP7**
		1	0	0	0	DTAS simulation	**WP7**
		3	0	0	0	Rocinante simulation	**WP7**
	2	0	0	0	0	**Data processing algorithm**	**WP7**
	3	0	0	0	0	**Documentation**	**WP7**
9	0	0	0	0	0	**Transportation**	**WP8**
	1	0	0	0	0	**Transport box for DTAS**	**WP8**
	3	0	0	0	0	**Transport box for Rocinante**	**WP9**

Planning of the upgrade of DTAS



Nom	Date de début	Date de fin	Durée
(NA)2STARS	02/01/2023	17/07/2026	925.0 day
Ganil scientific council	17/01/2023	17/01/2023	0.0 day
Scientific council decision	28/02/2023	28/02/2023	0.0 day
2023 Founding	28/03/2023	28/03/2023	0.0 day
2024 Founding	28/03/2024	28/03/2024	0.0 day
PAC Ganil	15/03/2023	15/03/2023	0.0 day
PAC Decision	26/04/2023	26/04/2023	0.0 day
technical discussion with Ganil	02/01/2023	24/03/2023	60.0 day
technical agreement Ganil (NA)2STARS	27/03/2023	27/03/2023	0.0 day
Design review LISE in 2024	01/07/2024	01/07/2024	0.0 day
Design review DESIR in 2025	06/07/2026	06/07/2026	0.0 day
Detector Power Supply	02/01/2023	19/06/2023	121.0 day
Low Voltage Power Supply	02/01/2023	19/06/2023	121.0 day
High Voltage Power Suppy	02/01/2023	19/06/2023	121.0 day
Readout electronics & DAQ	02/01/2023	11/08/2023	160.0 day
Global Design	02/01/2023	27/01/2023	20.0 day
Spectroscopy amplifier	30/01/2023	03/07/2023	111.0 day
DAQ system	30/01/2023	11/08/2023	140.0 day
Interface with beam system	27/03/2023	30/06/2023	70.0 day
Cables and connectors	30/01/2023	08/05/2023	71.0 day
DTAS for LISE	02/01/2023	04/12/2024	503.0 day
Simulation Geant4	02/01/2023	24/03/2023	60.0 day
Detection structure integration	02/01/2023	28/07/2023	150.0 day
Shielding	01/03/2023	18/07/2023	100.0 day
Table	01/03/2023	18/07/2023	100.0 day
Beam Tube for Lise	29/03/2023	05/12/2023	180.0 day
Design & integration DSSD	29/03/2023	15/08/2023	100.0 day
fabrication	16/08/2023	05/12/2023	80.0 day
Labr3_1	28/03/2023	09/10/2023	140.0 day
Order Labr3	28/03/2023	28/03/2023	0.0 day
Reception LaBr3	18/07/2023	18/07/2023	0.0 day
Test and calibration	18/07/2023	09/10/2023	60.0 day
LaBr3_2	28/03/2024	09/10/2024	140.0 day
Order LaBr3	28/03/2024	28/03/2024	0.0 day
Reception LaBr3	18/07/2024	18/07/2024	0.0 day
Test and calibration	18/07/2024	09/10/2024	60.0 day
Assembly and Test	10/10/2024	04/12/2024	40.0 day
DTAS Ready for LISE	05/12/2024	05/12/2024	0.0 day
DTAS for DESIR	05/01/2026	17/07/2026	140.0 day
Beam Tube for DESIR	05/01/2026	22/05/2026	100.0 day
Assembly & Test	25/05/2026	17/07/2026	40.0 day
DTAS Ready for DESIR	20/07/2026	20/07/2026	0.0 day
Rocinante for LISE	02/01/2023	10/10/2025	725.0 day
Rocinante for DESIR	13/10/2025	17/07/2026	200.0 day

Planning of the upgrade of *Rocinante*



Nom	Date de début	Date de fin	Durée
(NA)2STARS	02/01/2023	17/07/2026	925.0 day
Ganil scientific council	17/01/2023	17/01/2023	0.0 day
Scientific council decision	28/02/2023	28/02/2023	0.0 day
2023 Founding	28/03/2023	28/03/2023	0.0 day
2024 Founding	28/03/2024	28/03/2024	0.0 day
PAC Ganil	15/03/2023	15/03/2023	0.0 day
PAC Decision	26/04/2023	26/04/2023	0.0 day
technical discussion with Ganil	02/01/2023	24/03/2023	60.0 day
technical agreement Ganil (NA)2STARS	27/03/2023	27/03/2023	0.0 day
Design review LISE in 2024	01/07/2024	01/07/2024	0.0 day
Design review DESIR in 2025	06/07/2026	06/07/2026	0.0 day
Detector Power Supply	02/01/2023	19/06/2023	121.0 day
Low Voltage Power Supply	02/01/2023	19/06/2023	121.0 day
High Voltage Power Supply	02/01/2023	19/06/2023	121.0 day
Readout electronics & DAQ	02/01/2023	11/08/2023	160.0 day
Global Design	02/01/2023	27/01/2023	20.0 day
Spectroscopy amplifier	30/01/2023	03/07/2023	111.0 day
DAQ system	30/01/2023	11/08/2023	140.0 day
Interface with beam system	27/03/2023	30/06/2023	70.0 day
Cables and connectors	30/01/2023	08/05/2023	71.0 day
DTAS for LISE	02/01/2023	04/12/2024	503.0 day
DTAS for DESIR	05/01/2026	17/07/2026	140.0 day
Rocinante for LISE	02/01/2023	10/10/2025	725.0 day
BaF2 refurbishment	02/01/2023	31/12/2024	522.0 day
Simulation Geant4	01/01/2024	22/03/2024	60.0 day
Detection structure integration	01/01/2025	29/07/2025	150.0 day
Shielding	03/03/2025	18/07/2025	100.0 day
Table	03/03/2025	18/07/2025	100.0 day
Beam Tube for LISE	31/03/2025	15/08/2025	100.0 day
Assembly & Test	18/08/2025	10/10/2025	40.0 day
Rocinante for LISE Ready	13/10/2025	13/10/2025	0.0 day
Rocinante for DESIR	13/10/2025	17/07/2026	200.0 day
Beam Tube for DESIR	13/10/2025	27/02/2026	100.0 day
Assembly & Test	02/03/2026	24/04/2026	40.0 day
Rocinante for DESIR ready	20/07/2026	20/07/2026	0.0 day