EXPAND: *"Explorations at and beyond the neutron dripline"*

SUMMARY

The objective of the EXPAND project is to investigate, using the RIBF[1] facility at RIKEN (Saitama, Japan), the structure of light neutron-rich nuclei lying at and beyond the neutron dripline and to search for new phenomena. The RIBF provides unique possibilities for such experiments as it can provide the most intense secondary beams of light neutron dripline nuclei in the world – typically three or four orders of magnitude higher than any other facility.

The technical aspects of EXPAND focus on augmenting the neutron detection capabilities of the SAMURAI setup, which are critical to the study of nuclei at and beyond the dripline. Specifically the existing two-wall neutron array (NEBULA[2]) is being transformed by augmenting the number of scintillator modules and associated walls so as to create the NEBULA-Plus array. This will enable 3 and 4 neutron detection to be routinely possible, as well as increasing dramatically the single and two-neutron detection efficiencies.

The present document outlines the physics case for EXPAND. The status of the development of NEBULA-Plus as well as the experimental work that has gone on in parallel with the existing SAMURAI setup, including the NEBULA array supplemented with a NeuLAND demonstrator[3], is also presented.

INTRODUCTION & MOTIVATION

The exploration and understanding of the structure of the most neutron-rich nuclei is one of the primary goals of present day nuclear physics. The light mass region (A<40) offers the most promising possibilities in this respect: not only are a variety of well-developed theoretical models available (shell model, shell model in the continuum and various ab intio approaches), but from experimental point of view it has become possible to access nuclei at and beyond the neutron dripline. Importantly, these nuclei exhibit the most extreme neutron-to-proton ratios and, as such, provide some of the most severe tests of our understanding of the nucleus.

From a structural point of view, the light very neutron-rich nuclei exhibit a rich variety of phenomena, from evolving shell structure (including the development of new magic numbers) to neutron haloes and multi-neutron "skins". The physics objectives of EXPAND, as set out in detail a Letter of Intent written for the RIBF NPAC are, briefly enumerated, as follows:

- The exploration of multi-neutron unbound systems and the associated multi-neutron correlations in their decay. Of prime interest here are systems such as the most neutron-rich Oxygen isotopes ^{26,27,28}O. Most theories suggest that ^{26}O (unbound to 2-neutron emission) is only very slightly unbound, as indicated by work at the NSCL-MSU and confirmed with high precision by one of the SAMURAI "DayOne" experiments (see below). The observation of ^{28}O (4-neutron unbound) and the establishment of the character and location of the ground state is one of the long standing goals of

1 **R**adioactive **I**sotope **B**eam **F**actory
2 **NE**utron-detection system for **B**reakup of **U**nstable-Nuclei with **L**arge **A**cceptance
3 Elements of the neutron array currently being constructed for the NUSTAR setup at FAIR.

nuclear structure. Indeed ^{28}O is the last remaining classically doubly magic nuclei yet to be observed (Z=8, N=20) and is two protons removed from the N≈20 Island-of-Inversion[4].

In the very light mass region, much remains to be explored, including most significantly the structure of the heaviest hydrogen isotope, ^{7}H (4-neutron unbound), about which little is known other than a possible indication, from a measurement of very limited statistics, for its existence as a narrow resonance near threshold.

- Closely related to multi-neutron unbound nuclei is the investigation of multi-neutron systems. Given the very weakly (~100 keV) unbound character of the two-neutron system and the odd-even staggering in binding energies observed for the He isotopes it is possible that the 4-neutron system – or tetra-neutron – could manifest itself as a resonance in the continuum as hinted at in a recent measurement of the ^{8}He induced double-charge exchange on ^{4}He[5].

- The investigation of the low-lying level structures of neutron unbound systems. In the case of single-neutron unbound nuclei this not only provides insights into the evolution of shell structure far from stability into the continuum, but also provides critical input to define the core-neutron interaction for 3-body modeling of two-neutron haloes. In the case of two-neutron unbound nuclei, such as ^{16}Be, the possibility of direct di-neutron decay may be investigated.

- The investigation of the structure of and correlations in two-neutron halo systems and, ultimately, in multi-neutron haloes/skins (such as ^{8}He and ^{19}B). In addition to probing the spectroscopic configuration of the valence/halo neutrons, the long standing issue of the spatial correlations of the halo neutrons can be probed through, as for the two-neutron unbound systems, via the neutron-neutron relative momenta.

- The study of the continuum excitations of halo and other dripline nuclei. In particular, the low-lying excited state structure of these systems will be probed – eg., the location and transition strengths of the (unbound) first 2^+ states in even-even nuclei is a prime indicator of shell and sub-shell closures.

In order to undertake the investigations outlined the unique opportunities offered by the RIBF are exploited. Specifically the high intensity primary beams (including most significantly ^{48}Ca) coupled with the BigRIPS separator allow for the production of the most intense secondary beams of light neutron dripline nuclei in the world[6]. Moreover, in many cases, the RIBF is the only facility capable of producing these secondary beams. In addition, the beam energies (~250 MeV/nucleon) are ideally matched, both experimentally (thick targets, forward focusing of reaction products) and theoretically (eg., eikonal-type approaches), to the reactions – nucleon removal or "knockout", breakup, and inelastic scattering – that can be used to populate the final-states of interest.

As these states typically reside in the continuum, the experiments require, in addition to the detection of the charged fragment, the detection of one or more neutrons of beam velocity (β~0.6). The

[4] The so-called "Island-of-Inversion" where *νfp*-shell configurations dominant the ground states of the N~20 isotopes of Ne, Na and Mg.

[5] K Kisamori et al., Phys. Rev. Lett. **116** (2016) 052501

[6] For example, for ^{22}C and ^{31}Ne, at GANIL and RIKEN (prior to the RIBF), rates of some few counts per day were possible. In recent experiements rates of ~50 an ~10 pps have been achieved at the RIBF.

technical objective of EXPAND is to provide a multi-neutron (3 and 4n) detection capability whilst also augmenting significantly the single and two-neutron capability of the existing two-wall NEBULA array.

EXPERIMENTAL APPROACH

As noted, the experiments employ direct reactions – nucleon removal/knockout, breakup or inelastic scattering – of high-energy secondary beams. In general, as the final-states of interest are neutron (or multi-neutron) unbound, all the in-flight decay products (projectile-like charged fragments, neutrons and, in some cases, the γ-rays emitted by the excited core fragment) must be detected in coincidence and their momenta measured precisely. This permits the invariant mass spectrum to be constructed[7] (Fig. 1), together with other variables of interest, such as the neutron-neutron relative momenta.

Importantly, many of the investigations listed above can be undertaken in the same experiment. For example, reactions induced by a light target on a beam of a two-neutron halo nucleus (eg. ^{22}C) can be employed simultaneously to explore via neutron removal/knockout, the unbound A-1 subsystem (^{21}C) and via inelastic scattering the continuum states of the halo nucleus itself (eg., ^{22}C*(2$^+$)) and neutron-neutron correlations through the subsequent in-flight decay(^{22}C*$\rightarrow$^{20}C+n+n). In terms of the unbound (A-1) system (^{21}C), it may also be populated in a complementary manner – giving access to different states – via proton removal from the Z+1,2 nuclei (eg., one/two-proton knockout from ^{22}N/^{23}O).

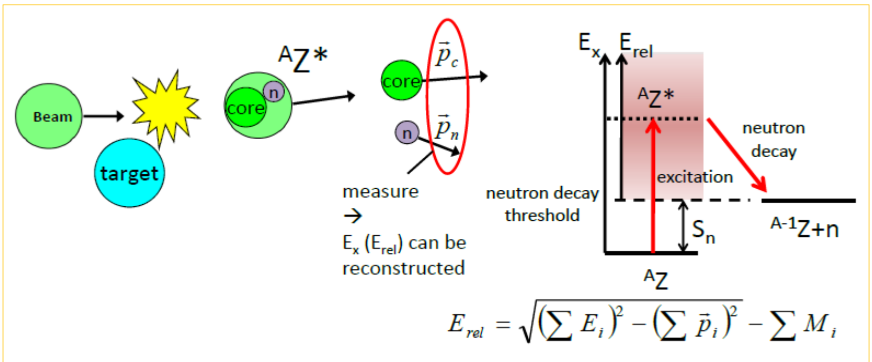

Figure 1: *The principles of invariant mass measurements of unbound states. For simplicity, the case of a single-neutron unbound state is shown.*

The principal elements required to perform such "kinematically complete" measurements at high energies are a large gap dipole magnet and associated focal plane detection system for the measurement of the beam-like charged fragments, and a multi-detector array for the beam energy neutrons emitted at forward angles. Figure 2 displays the SAMURAI setup at the RIBF when it was coupled with the NeuLAND demonstrator. The system comprises the superconducting SAMURAI dipole (7 Tm) and associated hodoscope and large area drift chambers and the two walls of the NEBULA plastic scintillator array as well as the 4 double planes of the NeuLAND demonstrator. When needed, the DALI2 NaI or CATANA CsI arrays may be positioned around the target to detect the γ-decay of excited core fragments. Of particular importance is the detection efficiency of the neutron array[8], as well as its ability to measure multiple neutrons, including those with small relative momenta. In the

[7] That is, the fragment-neutron(s) relative energy (E_{rel}) or energy of the system above threshold – ie., the decay energy (E_d).
[8] To first order a function of the total thickness of plastic scintillator.

case of multi-neutron detection, considerable care must be taken in identifying and rejecting cross talk[9].

The technology employed in the NEBULA array is relatively straight forward and consists of two walls, with each wall composed of two layers of long plastic scintillator bars. Each layer being composed of 30 bars. Each bar (180 x 12 x 12 cm^3) is in turn read out by two fast PMTs. The energy of the neutrons is determined by a measurement of the time of flight (ToF) with respect to a fast start detector placed just upstream of the target. The ToF, combined with the hit position in the array, provides for a determination of the momentum vector of neutron. Large area veto paddles positioned in front of each wall are employed to allow for the rejection of charged particles.

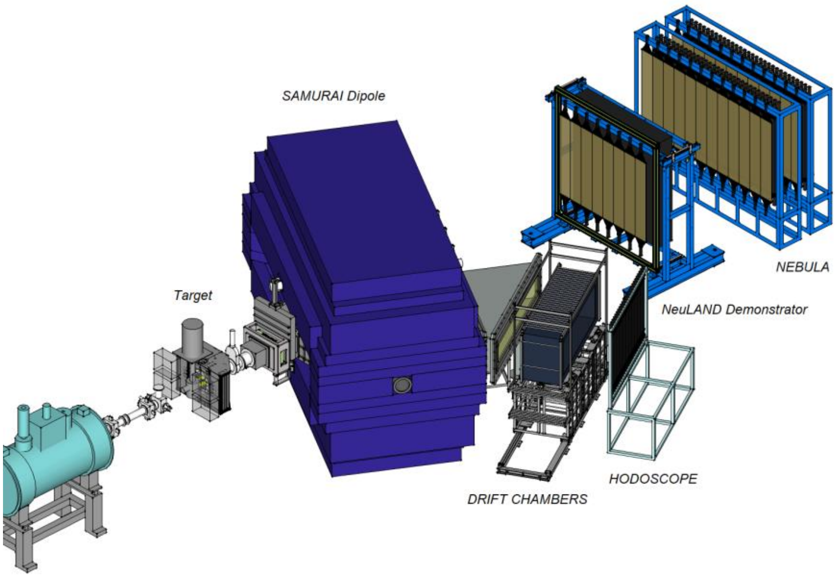

Figure 2: *View of the SAMURAI + NEBULA setup, including the NeuLAND demonstrator, for kinematically complete measurements of unbound nuclei.*

The strategy proposed in the context of the NEBULA array design to identify true multi-neutron events over cross-talk events is to employ multiple segmented plastic scintillator walls, to allow the inter-module or inter-wall velocity to be determined sufficiently precisely that true events may be separated from cross talk. The approach, a variant of which was developed by the LPC group for use at intermediate energies[10], relies on kinematic conditions[11] and, although resulting in a loss of some true events, ensures that essentially all cross talk events are rejected.

The SAMURAI setup, including the NEBULA array – using mono-energetic neutron beams produced via the ^{7}Li(p,n) reaction – was successfully commissioned in March 2012. This was then followed in the late spring by a campaign of three so-called “DayOne” experiments.

THE NEBULA-PLUS UPGRADE

The technical objective of the project is the transformation of the NEBULA array from its two-wall configuration to four walls (“NEBULA-Plus”). As outlined below, this will not only provide for the

[9] That is, instances in which a neutron scatters from one detector module to another, and deposits enough energy in each module such that an event is registered in both of them.
[10] FM Marqués et al., Nucl. Instrum. Meth. A450 (2000) 109
[11] T Nakamura, Y Kondo, Nucl. Instrum. Meth. B376 (2016) 156

capability to detect up to four beam velocity neutrons with good efficiency, but will also dramatically enhance the single and two-neutron detection efficiencies. Combining the NEBULA-Plus array with the SAMURAI spectrometer and the secondary beams provided by the RIBF will provide a unique world class tool to explore structure at and beyond the neutron dripline.

The funding to construct NEBULA-Plus is provided by the ANR as the EXPAND ("Explorations Across the Neutron Dripline") project. The goal of the project when first proposed to the ANR was to double the number of existing walls and detectors of NEBULA[12] – that is, four walls comprising a total of 240 modules (scintillator bar + 2 PMTs). Following the rejection of the original funding request (2013 and 2014), a scaled back project was proposed, whereby 90 rather 120 modules would be constructed and equipped with electronics. This would allow a 4-wall configuration with a somewhat reduced angular coverage to be constructed (as shown, for example, in Fig. 3) but still maintain very good efficiency gains (Fig. 4). This revised proposal was funded (2015), although with a budget reduced by 100 k€ with respect to the funding requested of 830 k€. This cut, combined with a large drop in the value of the Euro with respect to the US Dollar (all scintillator manufacturers are in the USA) lead to difficulties and considerable delays, in particular as possible alternative designs and solutions were sought.

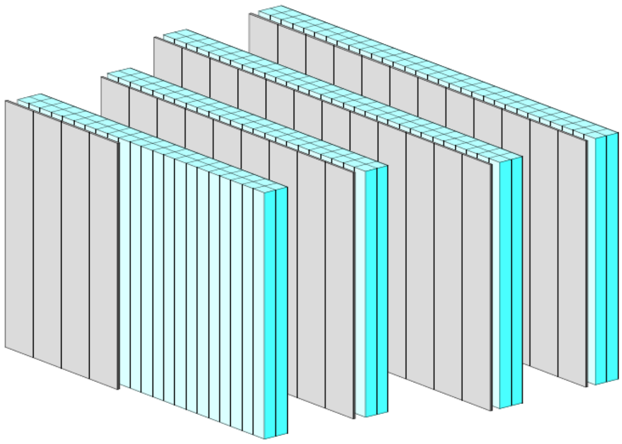

***Figure 3**: Schematic representation of the 4-wall (blue) configuration of the NEBULA-Plus (leftmost two walls – 90 modules) and NEBULA (120 modules) arrays. Also shown are the veto (grey) layers (partially removed on the first NEBULA-Plus wall).*

In this context, one promising possibility was the highly segmented NeuLAND design, incorporating low-cost PMTs and coupled to purposed built high density readout electronics. With the TU-Darmstadt group joining the SAMURAI collaboration, negotiations lead to a NeuLAND "demonstrator", composed of 4 double-planes[13] being installed at SAMURAI (Fig. 2) for almost 24 months. This allowed the design, optimised for operation at ~1 GeV/nucleon to be validated at RIBF energies (E_n~200 MeV), as well undertake certain elements of the physics programme outlined earlier.

Following a commissioning run in late 2015 which validated the operation of NeuLAND at RIBF energies, three successful campaigns of experiments were undertaken up until summer 2017, following which the demonstrator was returned to GSI/FAIR.

[12] NEBULA as shown in the accompanying figure is composed of two walls, with each wall composed of two layers of 30 detectors – ie., 120 detectors.
[13] Each double-plane being composed of two crossed planes, with each plane composed of 50 scintillator bars (250 x 5 x 5 cm^3), with each bar readout by two PMTs.

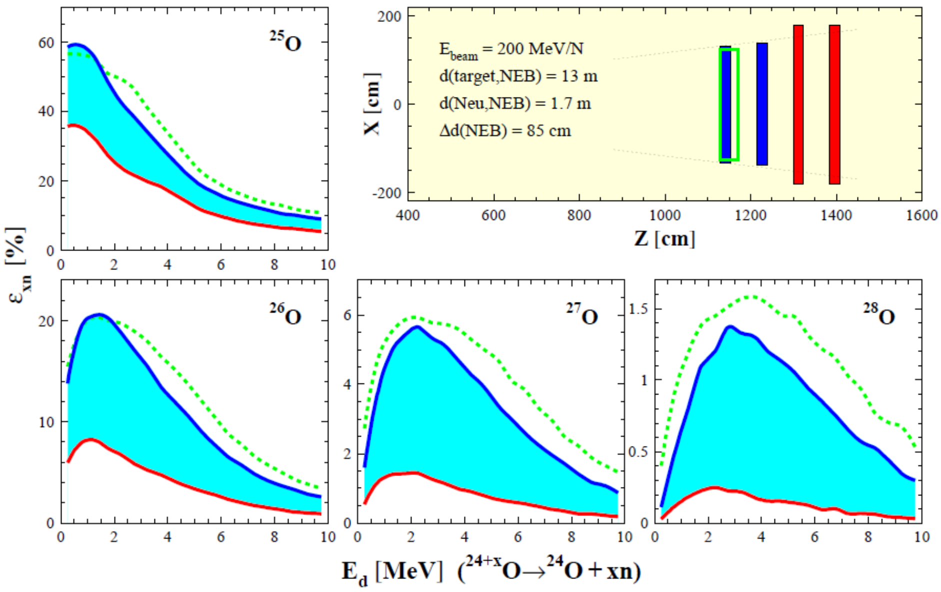

Figure 4*: Comparison of simulated neutron detection efficiencies for neutron multiplicities from 1 to 4 for NEBULA (red line), NEBULA+NEBULA-Plus (blue line, gain over NEBULA alone blue shading) and NEBULA+NeuLAND demonstrator (green).*

As outlined in the Annex, the final cost and significant issues with the readout electronics precluded a version of the demonstrator offering a viable solution for NEBULA-Plus. As a result the strategy was adopted in late 2017 to acquire 90 scintillator modules of the NEBULA design, including the PMTs (180), and to equip as many modules as possible within the EXPAND budget (60 – 70 detectors / 120 – 140 channels). Following the successful completion and testing of the array, the means to gradually equip all 90 modules over the next 2 – 3 years would be sought.

As illustrated in Fig. 4, 90 modules allows very significant gains to be made in the detection efficiency whilst retaining good acceptances. It is worth noting that the choice the NEBULA scintillator bar design for NEBULA-Plus offers the greatest possible flexibility for the future configurations of the array.

The status of the project, as of March 2019, is detailed in the accompanying Annex which was produced for the ANR as part of a request for an extension of the project's funding period. The request was granted and the revised completion date is 31 Dec 2020. As noted in the planning outlined in the Annex, this extension will facilitate the installation and cosmic ray/source testing and commissioning of the array and allows, if beam time is allocated by the RIBF management prior to Dec 2020, for the in-beam commissioning and first experiment to be conducted.

At the time of writing of this report all 91 scintillator modules have been delivered and 60 have been tested (all with good results). Around half the PMTs have been delivered and 40 have been tested using a source and small volume scintillator.

THE EXPAND COLLABORATION

The EXPAND-ANR collaboration formally[14] comprises groups from LPC-Caen, IRFU, IPN-Orsay, Tokyo Institute of Technology and RIBF-RIKEN. The ANR funding was provided to the 3 French groups, with the major part being allocated to the LPC group (which leads the project) in order to construct the NEBULA-Plus array. The main contribution of the IRFU team is the MINOS active liquid H_2 target[15]– the development of which was funded by an ERC grant – which importantly provides for a factor 5-10 gain in luminosity over standard solid targets (typically carbon) whilst still permitting good final reconstructed invariant mass resolution owing to the reaction vertex determination. The principal contribution of the IPN-Orsay team is participation in the experimental programme as well as in the installation and commissioning of NEBULA-Plus at the RIBF. The contribution of the Japanese teams[16], in addition to the experimental programme and installation of NEBULA-Plus, is that of on-site support as well as furnishing the mechanical support structures for the two additional walls and the veto layers and associated electronics, as well as the DAQ system.

A convention was signed by the 5 laboratories within the context of the ANR contract. It is envisaged that an MOU will be negotiated with the RIBF-RIKEN starting later this year when the array is ready to be transported to Japan. From an administrative point of view the array will be subject to the “permanent exportation” regime (ie., longer than 2 years) which requires that Japanese sales tax must be paid (~50k€).

HIGHLIGHTS OF THE PHYSIS PROGRAMME

As noted, a number of campaigns have been undertaken in recent years since the commissioning of the SAMURAI + NEBULA setup, including those with the NeuLAND demonstrator during the period it was installed at the RIBF. The following list is not exhaustive and concentrates principle on those experiments which were led by the French groups and/or had key input from the French groups.

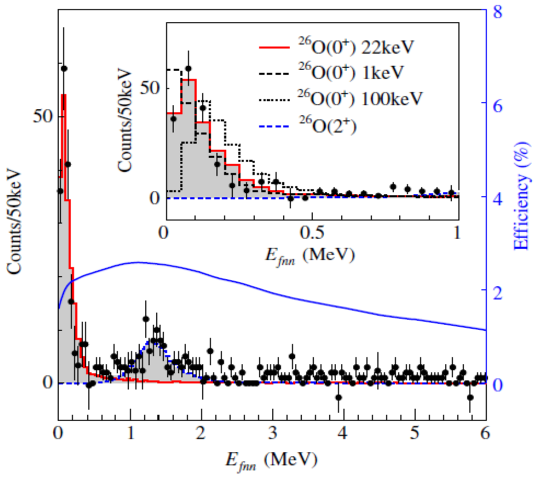

***Figure 5**: Decay-energy spectrum for ^{24}O+n+n events produced in proton knockout from a ^{27}F beam. The inset shows the threshold peak in detail, whilst the blue curve represents the detection efficiency*

[14] The running of experiments involves the much broader SAMURAI collaboration which includes a number of other Japanese institutes and universities (eg., Tohoku, Rikkyo and RCNP) , as well as other overseas laboratories, including TU-Darmstadt, GSI and SNU Seoul.

[15] A Obertelli et al., Eur. Phys. J. A (2014) **50**: 8

[16] The SAMURAI and NEBULA setup was funded by Japanese funding agency grants of around 10 M€.

- Investigation of two-neutron unbound system ^{26}O: this experiment was part of the DayOne campaign and led to the most precise determination of the binding energy of ^{26}O – unbound by only 18 keV – as well as the first observation of the excited 2^+ level (Fig. 5). Importantly, this work validated in the most extreme of cases (very low neutron-neutron relative momenta) the concept of the neutron array and the associated cross-talk rejection procedures.

  "The Nucleus ^{26}O: A Barely Unbound System beyond the Drip Line"
  Y Kondo et al., Phys. Rev. Lett. 116 (2016) 102503

- A spectroscopic study of the unbound systems in the region of N=14-16: using the complementary probes of proton and neutron removal/knockout, ^{21}C was identified for the first time and its low-lying level structure investigated (Fig. 6). The most complete spectroscopic studies to date were also carried out on the unbound levels of $^{17,19}C$ as well as the unbound B isotopes $^{16,18}B$. The work on the neutron-rich C isotopes confirm the theoretical predictions of degeneracy of the single-particle neutron $s_{1/2}$ and $d_{5/2}$ orbitals at Z=6.

  "Single-Neutron Knockout from ^{20}C and the Structure of ^{19}C"
  JW Hwang et al., Phys. Lett. **B769** (2017) 503

  PhD theses: S Leblond, LPC-Caen (Dec 2016); JW Hwang, SNU Seoul (August 2015),
  S Kim, SNU Seoul (August 2015)

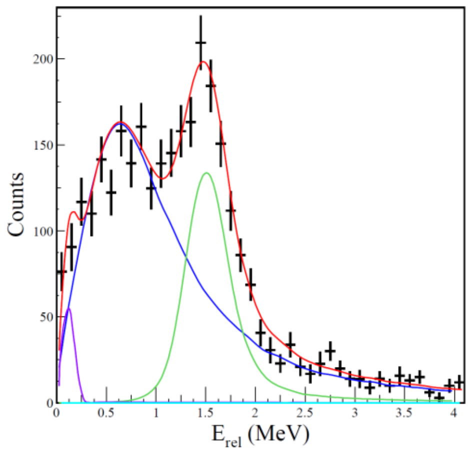

Figure 6: *Decay-energy spectrum for ^{20}C+n events produced in single-neutron removal from a ^{22}C beam. The broad structure at 0.8 MeV is identified as the $1/2^+$ ground state of ^{21}C whilst the peak at 1.5 MeV is the first excited $5/2^+$ state.*

- A determination of the total interaction cross section of ^{22}C: this work, as part of the DayOne experiments, provided the first precise determination of the size of ^{22}C – the heaviest known two-neutron halo and provided indirect insight into the importance of the contribution of the s-wave component of the valence neutron configuration to the halo.

  "Interaction Cross Section Study of the Two-Neutron Halo Nucleus ^{22}C"
  Y. Togano et al., Phys. Lett. **B761** (2016) 412

- The first observation of ^{20,21}B: in the context of one of the DayOne programme of experiments goals of exploring structure in the vicinity of N=14-16 below doubly magic ^{22,24}O, the heaviest boron isotopes to date were observed for the first time (Fig. 7). Clear resonance structures were observed for ^{20}B, while the data acquired for ^{21}B indicated that it is a candidate for direct two-neutron decay. Interestingly, all the structures observed in ^{20}B via the ^{19}B+n invariant mass lie well above the ^{17}B+3n decay threshold.

"First Observation of ^{20}B and ^{21}B"
S. Leblond, Phys. Rev. Lett. **121** (2018) 262502

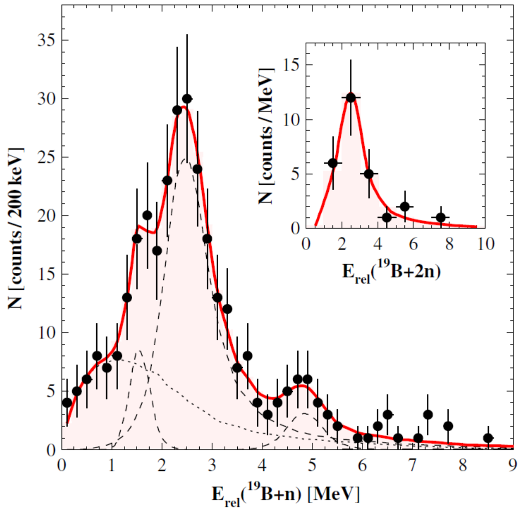

***Figure 7**: Decay-energy spectrum for ^{19}B+n events produced in two-proton removal from a ^{22}N beam. Inset: Decay-energy spectrum for ^{19}B+n+n events produced in single-proton removal from a ^{22}C beam.*

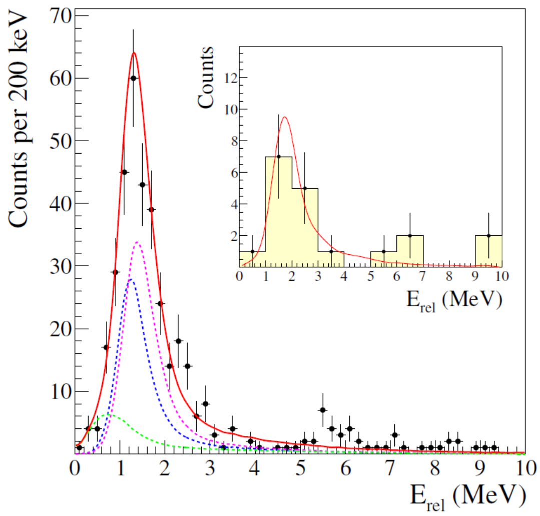

***Figure 8**: Decay-energy spectrum for ^{23}N+n events produced in two-proton removal from a ^{26}F beam. Inset: Decay-energy spectrum for ^{23}N+n+n events produced in two-proton removal from a ^{27}F beam.*

- The first observation of ^{24,25}N and the spectroscopy of ^{23}N: in a similar vein to the work on ^{20,21}B, the known isotopes of nitrogen have been extended one and two-neutrons beyond the dripline through the discovery of ^{24,25}N (Fig. 8). Interestingly, the latter, which may be viewed as a p-shell proton hole coupled to the ^{26}O ground state, is very much broader and significantly more unbound.

A study of the level structure of ^{23}N, employing a range of reactions, has confirmed that it has no bound excited states and that the first excited state – which may be viewed as a proton $p_{1/2}$-hole coupled to $^{24}O(2^+)$ – lies at relatively high excitation energy (3.5 MeV), suggesting the persistence of the N=16 sub-shell closure, albeit somewhat weakened with respect to ^{24}O.

PhD thesis: Q Deshayes, LPC (Dec 2017)

- The search for $^{27,28}O$ and the investigation of the very neutron rich F isotopes near N=20: this work employed the enhanced neutron detection efficiency offered by the coupling of NEBULA with the NeuLAND demonstrator as well as the MINOS liquid H_2 target and profited from advances in the ^{48}Ca primary beam intensity. The O data is under analysis (Tokyo Tech) and the almost finalised results are very encouraging and suggest that ^{28}O, as populated in proton knockout from ^{29}F, exists as a well-defined structure in the four neutron continuum.

  The investigation of the structure of ^{28}F through neutron knockout from ^{29}F provides clear indications that the ground state is dominated by intruder neutron *fp*-shell configurations, suggesting that ^{28}F lies within the Island of Inversion.

  PhD thesis: A Revel, GANIL-LPC (Oct 2018)

- An investigation of the two-neutron unbound system ^{16}Be: this experiment profited from a high intensity ^{17}B secondary beam coupled with the MINOS target to populate ^{16}Be via single-proton knockout. In addition to confirming an earlier observation of the ground state of ^{16}Be, the first excited (2^+) level has been observed for the first time (Fig. 9). Analysis of the ^{14}Be+n+n events demonstrate that the decay of both the ground and excited state are direct (no intermediate states in ^{15}Be appear to be fed). Comparison with realistic three-body modelling of the structure and decay of the ground state shows reasonable agreement between theory and experiment and suggests that the valence neutrons exist principally in a relatively compact "di-neutron" configuration and exhibit strong correlations in the decay of ^{16}Be.

  PhD thesis: B Monteagudo, LPC (Oct 2019)

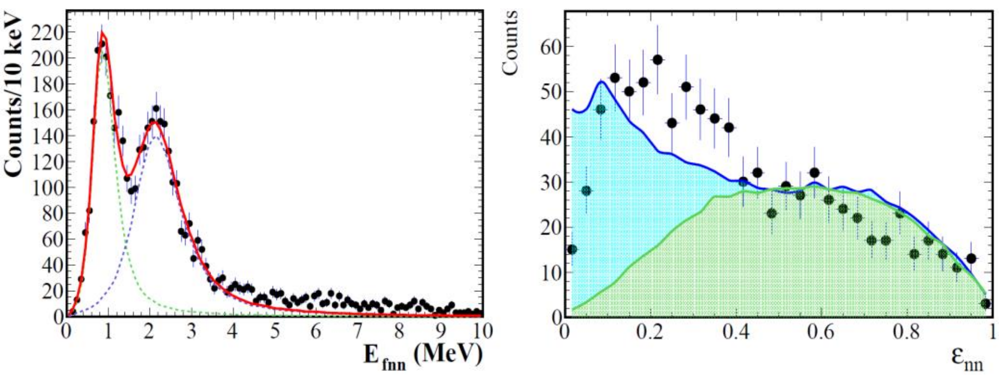

Figure 9: *Left: Decay-energy spectrum for ^{14}Be++n events produced in proton removal from a ^{17}B beam. Right: Renormalized neutron-neutron relative energy for the ^{16}Be ground state.*

- A search for the 4n system and the investigation of ^{7}H: as part of a campaign of experiments employing MINOS and the NeuLAND + NEBULA arrays, single-proton knockout from an intense ^{8}He beam has been measured with the goal of providing a definitive measurement of ^{7}H, whilst also searching for a possible ^{4}n resonance in its decay (t+4n). In parallel, a complementary measurement of the ^{8}He(p,2p) reaction via detection of the protons has been made using the proton tracking facility of MINOS together with a CsI array to determine the proton energies. Given the importance of this work and the difficulties in the analysis, especially of the 4n coincidences, parallel analyses are underway at LPC and the RIBF-RIKEN.

  PhD thesis: C Lenain, LPC (2021), S Huang, RIKEN (2021)

- Investigation of clustering in the neutron-rich Be isotopes: the $^{10,12,14}Be(p,p\alpha)$ quasi-free knockout reactions were studied using a thin solid H_2 target and the SAMURAI spectrometer and NEBULA array setup supplemented by detector arrays to determine the momenta of the knocked-out α particle and coincident proton. The data is in the preliminary stages of analysis.

  PhD thesis: P Li, HKU-IPNO (2022)

FUTURE PHYSICS PROGRAMME & DEVELOPMENTS

The physics envisaged with NEBULA-Plus will revolve in its initial stages around secondary beams derived from the ^{48}Ca primary beam, which in the last two years has been further developed through refinements in the ion source and accelerator operations such that intensities of up to 800 – 900 pnA[17] are available at BigRIPS. The first phase of experiments, within the context of the French collaborators, will most probably build on the work undertaken on structure in the vicinity of the N=16 subshell and N=20 shell closures. In this context a number of possibilities are being explored as noted briefly in the following. In the medium term, heavier mass systems, such as those in the vicinity of the N=28 shell closure, such as ^{39}Mg[18], may be focussed on.

- Search for excited states of ^{22}C: the availability of intense ^{23}N and ^{24}O secondary beams will allow the continuum states of ^{22}C to be investigated. In particular, the location of the first excited level (2^{+}) will provide direct insight into the strength of the N=16 sub-shell closure at Z=6, and as such will provide a good test of theory, including recently developed ab intio type calculations.

- Search for the direct di-neutron decay of ^{21}B and study of the 3 neutron decay of ^{20}B: the much improved multi-neutron detection efficiency and increased ^{22}C secondary beam intensity should allow a better than one order of magnitude improvement in the quality of the three-body coincidence data for ^{21}B[19]. Similarly the increased ^{22}N intensity and enhanced multi-neutron detection efficiency will allow the 3-neutron decay of ^{20}B (see above) and associated correlations to be investigated.

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[17] As compared to intensities of around 80 pnA during the DayOne experiments.
[18] An accepted proposal (LBL-LPC) to study the level structure of single-neutron unbound ^{39}Mg lapsed in 2017 owing to a then limited ^{40}Al beam intensity and neutron detection efficiency.
[19] Only some 25 events triple coincidence events were observed in the DayOne data.

- Search for ^{23}C and structure beyond N=16: an intense ^{26}F beam and enhanced neutron detection efficiency should allow ^{23}C to be discovered if, as predicted by mass surface systematics, it is unbound by ~2 MeV and exhibits a significant neutron $d_{3/2}$ valence neutron configuration.

  An alternative mechanism to populate ^{23}C may be investigated, if sufficient beam time is available: namely population via (^{12}C,^{12}N) charge exchange using a ^{23}N beam. Analysis of parasitic data acquired during the DayOne experiments suggest that such a charge exchange reaction is, in general, a viable alternative to multi-proton removal and may provide a means to populate different states.

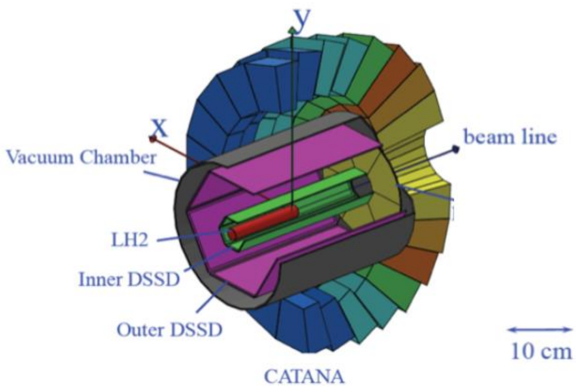

***Figure 10**: Conceptual design of Straβe coupled with the CATANA CsI array.*

Beyond completing the equipping of all the NEBULA-Plus modules with readout electronics, a number of technical developments are envisaged to enhance the overall SAMURAI setup and its performance.

In the medium term (3-4 years), a project has very recently commenced, led by Alexandre Obertelli (TU-Darmstadt), to improve considerably the reaction vertex reconstruction and proton trajectory determination for a MINOS-like liquid H_2 target. The proposal – "Straβe" – aims to employ, instead of the cylindrical TPC of the present MINOS system, a two layer barrel of double-sided Si strip detectors with 200 (inner) and 500 μm (outer) strip pitch (Fig. 10). The enhanced tracking is projected to improve the (p,2p) reaction vertex detection uncertainty to below 1mm (presently 5mm) with commensurate improvements in the proton trajectories, providing for a significant enhancement in the invariant mass resolution, as well as, when coupled to a detector such as the CATANA CsI array, determine the missing mass, independently of the neutron detection, with a resolution of order 1 MeV (FWHM). Such an improved vertex detection will allow for the exploitation of Ge arrays, rather than the DALI2 NaI array, for the detection of core fragment de-excitation γ-rays, which will be particularly important as the physics programme investigates higher mass systems with increased (core fragment) level densities.

The project is in a conceptual design stage, as depicted in Fig. 10. Partial funding has been acquired by TU-Darmstadt with a complement (150 k€) for some of the Si detectors to be provided through a 3 year "Chaire d'Excellence" very recently awarded to F Flavigny by the Normandy Regional Government. In this context F Flavigny will be joining the LPC group on a permanent basis in the late summer. Discussions have also begun between the LPC group and TU-Darmstadt to explore the possibility that the design and construction of the vacuum chamber and associated infrastructure be undertaken in Caen (with the capital costs provided by TU-Darmstadt).

Finally, although in the very preliminary stages of discussion, the use of the FASTER digital electronics for the NEBULA-Plus array has provided a trigger for discussions within the broader SAMURAI collaboration (in particular the RIBF, Tokyo Tech and Rikkyo members) on upgrading the SAMURAI DAQ system and electronics.

HUMAN & FINANCIAL RESOURCES

The source of financing for NEBULA-Plus has been the ANR funded EXPAND project. The total budget awarded by the ANR was 730 k€, of which overheads comprised around 30 k€. The remaining funds were allocated primarily to LPC - 648 k€ (essentially for equipment with some travel funded) - with IPN-Orsay allocated 18 k€ (primarily travel) and IRFU-Saclay 34k€ (to run and maintain the MINOS target system as well as travel). It may be noted that owing to the financial pressures on the project, the actual spending of the travel funds at LPC and IPN-Orsay has deliberately been limited as far as practically possible in order to conserve them for the installation and commissioning of NEBULA-Plus and therefore increase the effective equipment budget.

As such, the principal support for the SAMURAI based physics programme undertaken to date – essentially travel – has been the IN2P3 yearly grants as well as a lesser contribution from the Franco-Japanese LIA. Over the period 2015-18, the typical funding received directly from the IN2P3 has been around 20 k€ (depending on the number of experiments and physicists from LPC and IPN-Orsay implicated each year in the experiments) with an additional contribution from the LIA of some 3-6k€. In the case of graduate students, supplementary partial funding of order 1k€ has, on occasion, been provided by the graduate school of the Normandie Université.

In terms of manpower from the French laboratories, in the period 2015-18, the project has mainly been spearheaded by the LPC group with support for experiments employing MINOS provided by IRFU-Saclay and implication in some of the experiments by the IPN-Orsay group. In terms of IN2P3 supported manpower[20], typically some 5 to 6 FTE/year (physicists only, including PhD students) have been involved in the project and associated physics programme at SAMURAI. As noted in the ANR status report (Annex), one member of the LPC group (M Parlog) retired in Jan 2018. This loss in manpower will be compensated for by the arrival of F Flavigny at LPC later this year (0.5 FTE[21]). With the impending installation, testing and commissioning of NEBULA-Plus at the RIBF, additional support has been allocated by the IN2P3 in the form of a postdoctoral associate based at LPC. A candidate[22] has been selected and they will commence the 2 year position starting mid-October.

In terms of future requirements, the manpower that will be available by Autumn will be sufficient to accomplish the projects near and medium term goals – ie., installation, testing and commissioning of NEBULA-Plus at the RIBF as well as continuing the physics programme using the enhanced neutron detection capabilities. Continued support in terms of student fellowships – typically 1 every 2 years at each IN2P3 laboratory (LPC and IPN-Orsay) – is highly desirable.

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[20] For the university based physicists with teaching positions, full time research on the project is counted as 0.5 FTE.

[21] His research effort will be shared between the EXPAND/Straβe and GRIT projects.

[22] T Lokotkos – presently a research assistant at HKU Hong Kong with experience in radioactive beam experiments at the RIBF.

Financially, a modest increase in the IN2P3 support for travel to a minimum of 30 k€ per year, assuming an additional contribution of at least 5k€/year from the Franco-Japanese-LIA should be sufficient given the activities planned for the RIBF. It should be noted that with the installation of NEBULA-Plus and associated electronics, an increased presence at the RIBF will be required for all SAMURAI experiments employing fast neutron detection.

In terms of equipment funding, as discussed earlier and in the Annex, there will be a shortfall in the EXPAND ANR funding which will result in some 30 NEBULA-Plus detector modules not being equipped with the necessary readout electronics. The additional funding required is estimated to be 60k€. Preliminary discussions with the LPC management suggest that around half of these costs could be financed over the next 2 years from laboratory funds. As such, the remaining funds would be requested from the IN2P3 in 2020 and 21 (15 k€/year).

SWOT ANALYSIS

Strengths:

- RIBF's unequalled secondary beam intensities for light (A<50) neutron-rich beams.
- State of the art setup and instrumentation – in particular the SAMURAI spectrometer.
- Collaboration now very experienced in the simulation and analysis of complex experiments, including multi-neutron detection and cross talk analyses.
- French collaborators play key role in collaboration – reinforced with NEBULA-Plus.

Weaknesses:

- Shortfall in ANR funding.
- SAMURAI electronics and DAQ not state of the art.
- Limited beam time at RIBF (maximum of 4 months/year).
- Recent difficulties in procuring ^{48}Ca source material.
- Very limited theory support (France).
- Travel funds.

Opportunities:

- With successful commissioning of NEBULA-Plus the SAMURAI collaboration will be ideally positioned to play a leading role in neutron dripline physics for the next decade.
- Improvements possible with the Straβe active target.

Threats:

- FRIB (>2022) and to a lesser extent FAIR (>2025) – but relatively long lead times in ramping up beam intensities should be noted.

ANNEX

Report to the ANR 1 March 2019: Status of NEBULA-Plus

As indicated in the earlier interim reports (July 2016 and 2017) the project has suffered from a constrained budget owing to the funding awarded being reduced by 100 k€ with respect to that requested and, at the same time, a significant fall in the US dollar- Euro exchange rate (all plastic scintillator manufacturers are located in the USA). As also described, elements of the future highly segmented NeuLAND array (under construction for use at FAIR), forming a so-called demonstrator, were installed at the RIBF from autumn 2015 to summer 2017, following discussions with the TU-Darmstadt members of the SAMURAI collaboration. In terms of EXPAND, the objective[23] was to determine if the NeuLAND concept and design could be successfully employed at RIBF energies and, in parallel, undertake certain elements of the EXPAND physics programme.

As outlined in the July 2017 interim report, the NeuLAND demonstrator performed well and a number of experiments were performed, including the search for ^{28}O and the study of the most neutron-rich isotopes of F. Unfortunately, as detailed in the report, the high-density Tacquila electronics were found to present a number of significant issues in terms of their future use and would need to be replaced by a new design still under development at GSI with very long lead times. Furthermore it was not clear if a copy of the custom built high-density HV system (for the PMTs) could be acquired.

Moreover, given that the estimated cost of a NeuLAND-type demonstrator for NEBULA-Plus exceeded significantly (even under the most optimistic scenarios) the equipment budget for EXPAND, it was decided to fall back on the concept employing up to 90 scintillator modules (Figure 1) identical to that of NEBULA with the maximum number (60 – 70 modules) instrumented with readout electronics (see below) and HV within the present budget. This decision was made at the end of 2017. It is envisaged that following a successful commissioning funds may be sort over the following 2 to 3 years to incrementally instrument the remaining modules.

ELECTRONICS

In parallel to the discussions linked to this decision, it became apparent from some of the relatively high beam rate experiments that the standard VME readout electronics employed with the existing NEBULA array, was far from optimal and, in particular, acquisition dead time issues were being encountered. In addition, other features, including a very long delay required for the PMT signals used for the measurement of the energy deposited ("charge") in the scintillator bars, were also found to limit the performance of NEBULA. As such, solutions to improve the situation have been explored over the last 9 months.

Initial discussions suggested that a solution for both the time and charge measurements could be made (eliminating the delays and dead time limitations) by using a so-called QTC (charge-to-time converter) coupled to a multi-hit TDC. The only commercially available QTC which potentially met our needs – the "GeVγ-1370" from Fuji Diamond Ltd (Japan) – was coupled with a suitable multi-hit TDC (CAEN V1290) and tested with elements of the NEBULA array in autumn 2018. Whilst these tests illustrated

[23] For the NeuLAND collaboration, the goal was to test and operate the demonstrator with high-energy neutron beams owing to the long delays in the construction of FAIR (first beams expected in 2025).

that a QTC–multi-hit TDC combinations offered in principle a possible solution, in practice major modifications to the QTC would be required before it could be considered as a viable and long term option.

At present, two options are being explored: 1) a VME QDC (produced by Mesytec) with delayed signal gating and 2) the utilisation of the FASTER digital electronics (developed at LPC-Caen). Tests underway at the RIBF (VME) and at LPC (FASTER) will enable a decision to be made by the end of April. In terms of the long term future of work at the RIBF, introducing the digital electronics option is felt to be the more attractive option, provided that the system, normally intended as a free standing triggerless system, can be integrated into the SAMURAI DAQ.

Assuming that we are able to place the orders for the chosen electronics option in May-June, we expect to be able to take delivery by November.

SCINTILLATOR MODULES

Following the decision to acquire 90 scintillator modules (scintillator bars + two light guides with reflective and protective opaque wrapping) of the NEBULA design, discussions were opened with possible suppliers in late 2017. Some difficulties were encountered in having the light guides fabricated as single elements. In addition, lengthy discussions were needed to agree on the best and most cost effective techniques for the final finishing of the surfaces of the scintillator modules.

Official price quotations were provided by St Gobain Crystals (USA) , Scionix (European representative for Eljen-USA) and Rexon (USA), with the former two being the most competitive. As required by the CNRS procurement rules, the supply of the 90 modules was sent out for official tenders. The offer from Scionix was subsequently selected and the order placed with them (October 2018) at a total cost of 258 k€[24].

The scintillator modules will be delivered to LPC where a dedicated test bench has been fabricated (Fig. A1), whereby each module will undergo acceptance tests – charge and time measurement performances will be determined using an AmBe source and cosmic rays.

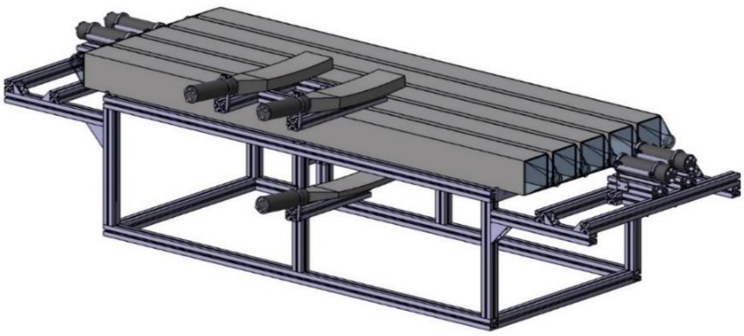

***Figure A1**: The scintillator module test bench setup at LPC with 5 NEBULA-Plus modules. The short scintillator bars are used to define the trajectories of the cosmic rays.*

[24] Price for 91 modules – one module will be kept at LPC as a reference and for future testing and R&D.

The fabrication and preparation of the first batch of 20 scintillator modules by Eljen (USA) has taken considerably longer than originally planned. This batch (Fig. A2) was shipped from the Eljen factory in Texas in mid-Febuary and will be checked and undergo optical transmission tests by Scionix (Netherlands). Delivery is to LPC expected in early March. Four further batches (3 x 20 and 1 x 11 modules) are expected to be delivered to LPC at roughly 2 week intervals, with the final delivery being made by mid-April.

PMT ASSEMBLIES

The PMT assemblies[25] (Hamamatsu model H11284) were ordered in November 2018 from Hamamatsu-France – total cost 124 k€ for 180 units. The final mounting on the scintillator modules will be done at the RIBF. Acquiring the PMTs separately, rather than as part of fully completed scintillator detectors (as originally envisaged), has allowed for cost savings of some 10% on the total cost of each completed scintillator module.

***Figure A2**: The first batch of scintillator modules being prepared for shipping at the Eljen factory (12 Feb 2019).*

The acceptance tests will be undertaken with two matched H112814 PMT assemblies which have already been acquired from available stocks at Hamamatsu-Japan. Based on the updated delivery schedule from Eljen and Scionix (see above) it is expected that the acceptance testing should be completed by August.

Some delays have occurred in the manufacturing of the 180 H11284 PMT assemblies required for NEBULA-Plus. The present delivery schedule foresees the first batch of 20 PMT assemblies being delivered in late March. Five further batches are slated to be delivered at approximately 1 month intervals with the final delivery of 40 assemblies planned for September. The operation of all PMT assemblies will be checked at LPC before their preparation for shipment to the RIBF-RIKEN.

[25] PMT and voltage divider unit.

The high voltage power supplies for the PMTs will be purchased from CAEN. In order to ensure full compatibility with NEBULA – notably in terms of spare HV cards – the same system (CAEN model SY1527) as already in use with SMAURAI will be acquired.

SHIPPING TO JAPAN, INSTALLATION AND COMMISSIONING

Based on the delivery and testing schedules (scintillator modules and PMT assemblies) as well as the timeline for a decision on the readout electronics and its purchase, it is currently planned to ship NEBULA-Plus to RIKEN in November – December.

We note that we have been advised by the CNRS (Normandy Regional Office) and the IN2P3 that, owing to issues surrounding CNRS internal billing and accounting and the ANR rules, we are unable to use the services of the IN2P3 logistics group ULISSE for the shipping and clearance of customs in Japan[26]. As such we have sort funding for this (on the order of 25 k€) from the IN2P3 and LPC. It is worthwhile noting that while no import duty is expected to be charged by the Japanese authorities, as NEBULA-Plus will be sent on a permanent export basis (ie., longer than 2 years) we are liable to pay Japanese sales tax, which is presently 8%[27]. As such we have set aside 50 k€ to cover these costs (which were included in the cost estimates for each major element of NEBULA-Plus in the original ANR funding request).

The installation of NEBULA-Plus is currently planned for January-March 2020 (beam at the RIBF is not expected to start before mid-March). Provided that no major problems are encountered, testing and commissioning with sources and cosmic rays should take place in April-June together with integration of the NEBULA-Plus readout electronics into the SAMURAI DAQ.

Whilst it is too early to engage in detailed discussions with the RIBF management, it appears feasible to envisage in-beam commissioning[28] of NEBULA-Plus during the Autumn beam period[29] of 2020 (October-November). Ideally this would be coupled with a first SAMURAI experiment incorporating NEBULA-Plus. The situation should become clearer towards the end of this year when the RIBF's strategy for the beams that will be run in 2020 is finalised.

PERSONNEL

The LPC group, which is the team primarily responsible for the construction of NEBULA-Plus, has had to grapple with a number manpower issues since the last report in July 2017. Specifically:

- Franck Delaunay has been, for personal/family reasons on study leave and sabbatical in Turin since November 2017. He will return to the group in July. During his absence Franck has continued to contribute where possible to the project, most notably by his involvement in the testing of the QTC.

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[26] ULISSE has preferential rates negotiated with selected transport companies as well as an import broker in Tokyo.
[27] A rise to 10% has been announced for 2019, although the situation is unclear as this change has already been postponed on at least 2 occasions.
[28] Using the ^{7}Li(p,n) reaction to produce a monoenergetic beam of neutrons.
[29] The RIBF does not run high-energy beams from the SRC cyclotron in the winter (Dec-March) or summer (July-August).

- Lynda Achouri has been on medical leave, owing to a serious health issue, since May 2018. She has very recently returned to LPC on a halftime basis pending further improvements in her health.

- Marian Parlog retired in January 2018. His request to prolong his career, as originally envisaged in terms of the completion and commissioning of NEBULA-Plus, for a further 2 years (to the age of 67) was, unfortunately, denied by the CNRS for administrative reasons[30].

Owing to the difficulties that this loss in manpower has caused over the last 12-18 months (in particular as Delaunay and Parlog were the group's principal technical experts on neutron detectors) a request for a postdoctoral fellowship was made in 2018 to the IN2P3 to support EXPAND. This postdoctoral position (2 year duration) has very recently been awarded to the group and a search is presently underway with a planned start date of Sept-Oct 2019.

In parallel, Freddy Flavigny (CR-CNRS, IPN-Orsay) has, in collaboration with the LPC group, applied for a 3 year "Chaire d'Excellence" funded by the regional government of Normandy. Dr Flavigny's application has been selected and he should begin working with the group in October 2019 when his permanent transfer to LPC is completed. Importantly, one of the two major axes of his research project involves collaboration with our SAMURAI partners from TU-Darmstadt and the Tokyo Institute of Technology on the development of a new active liquid H_2 target concept for SAMURAI experiments (an important contribution to the long term physics goals of EXPAND). As such, and as a member of the LPC group, he will be involved in various aspects of the installation and commissioning of NEBULA-Plus.

We note that, as outlined in the original EXPAND funding request, the Tokyo Institute of Technology, RIKEN Nishina Center and IPN-Orsay collaborators will be involved in the installation, testing and commissioning of NEBULA-Plus at the RIBF.

[30] His date of birth fell in a transition period with respect to the change in the retirement age to 67.