ACTAR TPC @ TRIUMF

T. Roger
GANIL (France)

B. Fernández-Domínguez
IGFAE-University of Santiago de Compostela (Spain)

G. Grinyer
University of Regina (Canada)

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Abstract

The present document describes the scientific motivation for performing a campaign of experiments at ISAC-II using the Active Target and Time Projection Chamber (ACTAR TPC) that was designed, constructed and commissioned at GANIL in France. Our intent is to ship the entire detection system (detector, electronics, power supplies, computers, data disks and cables) to TRIUMF and capitalize on some of the unique beam capabilities that are available at the ISAC facility.

1 The scientific scope of the project

Nuclear structure at, and beyond, the driplines exhibits interesting features such as single and multi-nucleon halos, proton radioactivity, or cluster structures. Furthermore, light nuclei far away from stability show a large isospin asymmetry that modifies the residual interaction at the drip-lines. The theoretical knowledge of exotic nuclei constitutes one of the main subjects in nuclear physics research nowadays. Light exotic nuclei show important features that differ from the usual shell structure observed near stability [1, 2, 3]. Furthermore, near and beyond the drip line, other effects become important including three-body correlations [4, 5, 6], and the influence of the scattering to the continuum in weakly bound and unbound states [7, 8, 9]. Research of the structure of exotic systems will provide new insights into the nuclear force as we approach the driplines. They also hold crucial information for understanding the formation of heavy elements in stars through the HCNO cycle.

Experimental and theoretical information on these nuclei is scarce. A major challenge facing experiments with rare-isotope beams concerns the need to detect and quantify reaction and decay products using only limited numbers of ions. The use of a gas volume that serves as both a sensitive detector and as the target itself (an ”active target”) thus offers significant advantages over traditional experiments. With its intrinsic high detection efficiency, excellent angular and position resolution, and its ability to reconstruct the kinematics of every event in three dimensions, a gas-filled detection system such as ACTAR TPC plays a vital role in future studies of the most exotic nuclei (Figure 1). Two main modes of operation are commonly used with ACTAR TPC either reaction mode or decay mode. For the TRIUMF campaign, ACTAR TPC will operate essentially in the reaction mode. ACTAR TPC is particularly well suited for direct and resonant reactions induced by radioactive beams.

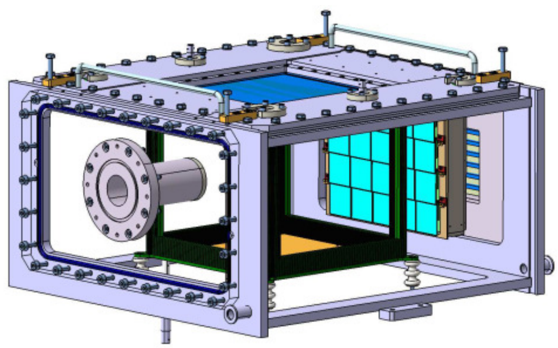

Figure 1: Schematic layout of the ACTAR TPC detector.

ACTAR TPC has been commissioned in 2017 using resonant scattering of an accelerated ^{18}O beam on an isobutane gas (proton) target [10]. The analysis of the reactions ^{18}O(p,p)^{18}O and ^{18}O(p,α)^{15}N showed that resolutions on the center-of-mass energy of the order of 38(4) keV FWHM for the (p,p) channel and 54(9) keV FWHM for the (p,α) channel can be easily achieved. In 2022, the first transfer experiment with ACTAR TPC was performed and the results proved the enhanced capabilities of the experimental setup for these type of measurements. Many successful results have also been obtained with ACTAR TPC in the decay mode but they will not be discussed at this scientific council.

2 The scientific project itself : ACTAR TPC at TRIUMF

The beams from TRIUMF combined with ACTAR TPC will be used in a very rich scientific programme. Two experiments were approved by the EEC scientific council at TRIUMF in 2019 and reapproved in 2022. Another was submitted in December 2023. The motivation is to use ACTAR TPC at TRIUMF and profit from the unique beams produced at the ISAC-II accelerated beam facility. The approved experiments requested beams of ^{17}F and ^{20}Mg with intensities of 5000 pps and 3000 pps, respectively. Neither of these beams can presently be produced at GANIL with the intensities required for the experiments. The new experiment is requesting a beam of ^{11}Li, which is also not available at GANIL.

- **S2008 : Study of the unbound states in ^{21}Al using an active target.**
  Spokespersons: B. Fernández-Domínguez (IGFAE-USC), T. Roger (GANIL) and O. Tengblad (IEM). *(Approved with high-priority in December 2021)*

  This experiment was originally approved by the ISOLDE PAC in June 2012 but was not performed because the final detector was not operational until 2017. Later, the beam intensity at ISAC-II was shown to be much higher, by approximately two orders of magnitude, than at ISOLDE. In addition, the continuous beam structure available at ISAC-II was proved to be much more convenient and better adapted for active targets. The proposal was therefore submitted to the EEC-committee in TRIUMF in December 2019 for the first time and resubmitted in December 2022 because no shifts had been taken owing to COVID-19 pandemic.

  This experiment requires a total of 21 shifts ($\simeq$ 7 days, 8-hour shifts) of ^{20}Mg beam from ISAC-II with a beam intensity of only 3×10^3 ions/s at two different energies : $6A$ MeV and $2A$ MeV. Ganil production for ^{20}Mg at the same energies is expected to be a factor 10-100 lower.

- **S2029 : Resonant proton elastic scattering on ^{17}F.**
  Spokespersons: G.F. Grinyer (U. Regina) and T. Roger (GANIL).
  (Approved with high-priority in December 2021)

  This experiment was approved by the GANIL PAC in April of 2016 but could not be scheduled because the ^{17}F beam needed to perform the experiment could not be developed at SPIRAL1 due to technical issues associated with the FEBIAD ion source. This experiment expired (automatic 3-year removal from the list of approved experiments if not run) and was not re-proposed since fluorine beams were not available at SPIRAL1. Since the ^{17}F beam was already available at ISAC with sufficient intensity and purity, the experiment was proposed as one of the main drivers for the ACTAR TPC campaign at TRIUMF.

  This experiment requires a total of 16 shifts ($\simeq$ 5 days, 8-hour shifts) of pure $^{17}F^{9+}$ beam from ISAC-II with a beam intensity of only 5×10^3 ions/s.

- **S2384 : Detailed spectroscopy of ^{12}Li using the (d,p) reaction with ACTAR TPC.**
  Spokespersons: B. Fernández-Domínguez (IGFAE-USC), W. Catford (U. Surrey) and T.Roger (GANIL).
  (Submitted in December 2023)

  This experiment was presented at the past December call. The experiment requested a total of 24 shifts ($\simeq$ 8 days, 8-hour shifts) of ^{11}Li from ISAC-II with a beam intensity of 3×10^3 pps at $7.5A$ MeV. The requested beam is presently not available at GANIL.

In summary, a total of 37 shifts of 8 hours have been already allocated to the ACTAR TPC collaboration in TRIUMF with high priority. This amounts up to 12.3 days of beam time. If the S2384 experiment is approved then a total of 61 shifts and 20.3

days. It is important to note that both approved experiments (S2008 and S2029) will expire in December 2025.

In the following sections, we will briefly outline the scientific relevance of the approved and submitted experiments.

2.1 S2008 : Study of the unbound states in ^{21}Al using an active target.

The experiment aims at studying the spectroscopy of ^{21}Al for which experimental information is not available. Exotic nuclei far away from stability show a large isospin asymmetry that modifies the residual interaction at the drip-lines. Sizeable effects of these modifications are: the Thomas-Ehrman Shift (TES), which produces a displacement in the energies of mirror nuclei and the ground-state energies and excitation spectra of proton-rich nuclei along the N=8 chain. The incorporation of three-body forces (3N) is expected to provide repulsive contributions to neutron-deficient nuclei [11] as seen in the case of the oxygen neutron-rich nuclei. Current studies of chiral 3N forces for the N=8 isotones place the ^{22}Si isotope at the proton dripline [11]. The N=8 shell gap in light medium-mass proton rich nuclei is only known up to ^{20}Mg, the next isotope in the chain is the ^{21}Al. In addition, the evolution of the neutron shell gaps from N=20 to N=16(14) observed experimentally is known to be due to the modification of the single-particle properties in light neutron-rich nuclei by the combined action of the central component and the tensor part of the effective nucleon-nucleon (NN) interaction [12, 13, 14]. Based on charge-symmetry of the nuclear force, one would expect that replacing neutrons by protons a similar trend in the mirror proton-rich systems should emerge. The ^{20}Mg+p reaction will populate the proton-unbound states in ^{21}Al, which is a N=8 isotone, using the inverse kinematics thick target scattering method. The experiment will measure: the location of the low-lying states in ^{21}Al that will bring crucial information on the Thomas-Ehrman shift between mirror pairs, the size of the Z=20 and Z=16 shell gaps at N=8 as well as an important test for 3N forces. Investigation via inelastic scattering will provide access to the strength of core excitations and will allow to prove the existence of narrow unbound resonances beyond the proton drip-line.

2.2 S2029 : Resonant proton elastic scattering on ^{17}F.

The experiment plans to use a mixture of isobutane and hydrogen gases in the detector to create a thick proton target. A radioactive beam of ^{17}F ($T_{1/2}$ = 65 s) will impinge the gas target at an energy of approximately 5*A* MeV. Unbound states in ^{18}Ne will then be populated via resonant proton elastic scattering and will subsequently decay by (primarily) proton emission back to the ground state or excited states in ^{17}F. The experiment focuses on a single resonance in ^{18}Ne, which is the 1^- resonance at 6.15 MeV. This resonance is crucial for evaluating the ^{14}O(α,p)^{17}F reaction rate, which is one of two break-out pathways from the HCNO cycle in explosive astrophysical scenarios [15, 16]. Presently, this resonance is known to decay by proton emission but both the decay and the 2-proton emission channels are opened. Previous experiments have suggested that the 2p channel may be as large as 27% [17], which, if true, would dramatically alter the astrophysical importance of this resonance. Theoretical estimates for 2p emission are about 4 orders of magnitude smaller [18]. One reason for this discrepancy may be because the decay of the 6.15 MeV resonance by α or by 2p emission have never been measured directly but only inferred from indirect experimental observables and arguments based on mirror symmetry. The goal of this experiment is to populate this resonance using the ^{17}F+p reaction in inverse kinematics and use the 3D tracking capabilities of the TPC to directly observe the 2p and α-particle tracks, which would be easily distinguishable from high-energy protons produced from elastic and inelastic scattering. This measurement would provide the branching ratios for these two decay modes (or set limits on them if they are negligible) and would therefore clarify their importance in astrophysical environments.

2.3 S2384 : Detailed spectroscopy of ^{12}Li.

The experiment intends to measure the structure of ^{12}Li via one-neutron transfer reaction with an active target. The aim of the experiment is to measure the location of the first *p* and *d*-wave resonances and deduce the nature of the low-lying states in ^{12}Li. The measured states will provide key information on the parity inversion at N=9. The structure of ^{12}Li constitutes a theoretical challenge. The study of the low-lying states in ^{12}Li, being dominated by excitations of a ^{9}Li core and three neutrons, will provide an stringent test for three-nucleon body forces. Combining the unique ^{11}Li beam available at TRIUMF and the enhanced capabilities of ACTAR TPC, the expected yield will be increased by at least 1 order of magnitude pushing the limits of resolution and sensitivity at hand with standard techniques.

3 Collaboration and its implications in the project

The ACTAR TPC collaboration is composed of about 25 permanent researchers (plus about 10 PhD students and postdocs), from 10 laboratories: GANIL (Fr), LP2IB (Fr), IGFAE-USC (Es), U.Regina (Ca), KUL (Be), CEA/IRFU (Fr), IJCLab (Fr), RIKEN (Jp), LNL (It), and UHU (Es). The collaboration is organized through a collaboration agreement in which decisions are taken with majority votes. The decision to propose a campaign of measurement in TRIUMF (Canada) has hence been voted by all parties. For this campaign, 2 experiments were accepted so far at the TRIUMF EEC. The first experiment is a joint proposal between IGFAE-USC, GANIL and IEM (B. Fernández Domínguez, T. Roger, O. Tengblad) . The second experiment is lead by U.Regina and GANIL (G.F. Grinyer, T. Roger). Hence, three of the parties (U.Regina, IGFAE-USC, and GANIL) are de facto strongly involved in the present project.

4 Timeline

The outline of the project was presented to the EEC scientific committee in July 2019 as a Letter of Intent (S1931LOI) and was endorsed with high priority at the EEC meeting. From this strong endorsement from the TRIUMF science committee, two experiments have since been approved (S2008 and S2029) and a third experiment (S2384) has just been submitted at the last EEC call. Successful commissioning of the ACTAR TPC detector took place in 2017 and resulted in the publication [10]. ACTAR TPC is now in a data-taking phase. The first physics campaigns took place in GANIL in 2019-2022[1]. Five different experiments were performed during this period:

- E690 : Proton decay branches of ^{54m}Ni and ^{53m}Co, which lead to 4 publications in peer-review journals [21, 22, 23, 24].
- E780: Study of giant resonances in exotic Ni isotopes at LISE, which is currently under analysis in CEA Saclay and KULeuven.
- E796: Study of the $1p_{1/2} - 1p_{3/2}$ spin-orbit splitting in ^{19}N. The experiment is under analysis at the IGFAE-USC. The data analysis is partly completed. One article is being written and 1 Ph.D thesis was defended.
- E791: Two proton radioactivity of ^{48}Ni. The analysis of experiment is currently being finalized at LP2IB, and 1 Ph.D thesis was defended.
- E823: Coulomb excitation and inelastic proton scattering of neutron-rich Si isotopes between N=20 and N=28. This experiment is currently under analysis at LP2IB and at IFJ.

Another physics campaign is planned at GANIL in 2024 with two experiments scheduled to take advantage of the SPIRAL1 beams:

- E785S: ^{12}Be structure in multi-threshold vicinity: search for narrow resonances, using the ^{8}He+α resonant reaction
- E864S: Measurement of ^{8}Li(α,n)^{11}B cross section with ACTAR, using a newly developed ^{8}Li beam

The performance of the detector was optimized in the 2019-2022 campaign. However, several upgrades are foreseen for the campaign at TRIUMF including:

1. Optimise the gas recycling system so as to ameliorate the mobility of the setup.
2. Improve the dynamic range and angular coverage of the ancillary detectors.
3. Enhance the amplification capabilities by using GEM-like devices.

The gas recycling system, financed by the Région Normandie, consists of a commercial gas filter coupled to the classic gas regulation unit used on ACTAR. Straight forward modifications have been applied to the gas circuit in order to make possible the re-circulation of gas in the detector. The tests performed at GANIL have shown that this system permits to have a constant gain in the detector over a period of more than 10 days, with a single volume of gas.

New silicon pad detectors 1.5mm thick were funded by the Spanish Ministry of Science and Innovation. The PCBs have been designed at IGFAE-USC with the aim

[1]Some of the experiments had to be rescheduled due to the COVID-19 pandemic

of optimising the interspace between the sensors. The collaboration owns most of the electronic chain and only two preamplifiers will need to be purchased for the new detectors. Test of the silicon detectors will be performed at the IGFAE-USC before shipping them to TRIUMF.

Additionally, the detector will be equipped with a multi-layer thick GEM (ML THGEM) device that allows to operate the detector with pure noble (or diatomic) gases. The DAQ system will benefit from the use of a new computer with faster processors. It is important to note here that the proposed experiments can be performed without the aforementioned upgrades. Discussions with our partners in TRIUMF are starting to sign an MoU before shipping the detector there.

Figure 2 shows the timeline for the ACTAR TPC collaboration over the next three years. In 2024, during the first two quarters of the year, ACTAR TPC will be placed at GANIL for running the scheduled experiments. In the third quarter of 2024, the remaining upgrades will be incorporated to the existing ACTAR TPC and tests will be performed before sending it to TRIUMF. The shipping of the entire detector together with the ancillary silicon detectors and the associated electronics is foreseen in the last quarter of the 2024. The mounting of the detector in TRIUMF is planned during the first quarter of 2025 and the collaboration intends to request the shifts during the second and/or third quarter of 2025. The full setup will be back at GANIL in autumn 2025 ready for the next campaigns at RIKEN or GANIL depending on the facilities schedule.

TASK	2024				2025				2026			
	T1	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3	T4
Campaign GANIL	X	X										
Upgrades and tests			X									
Preparation & Shipping to TRIUMF				X								
Mounting at TRIUMF					X							
TRIUMF Campaign						X	X					
Return to GANIL								X				
RIKEN/GANIL Campaign									X	X	X	X

Figure 2: Timeline for the ACTAR TPC collaboration over the next three years.

5 Budgetary overview, including possible external sources of funding

The human resources in place for the ACTAR TPC campaign in TRIUMF are outlined below in one month-Full Time Equivalent (1mFTE):

5.1 Human resources

- **GANIL** : 1 senior, 2 engineers , 0.5 technician.
- **IGFAE-USC** : 1.5 seniors , 0.6 technician, 2.5 students
- **U. Regina** : 1 senior, 2 students
- **TRIUMF** : 1 senior, 1 technician

According to the beam time allocated, the campaign might last between $\simeq$ 13 or 20 days. Taking into account the mounting time, the full campaign is estimated to last two months at maximum. The main bulk of human resources for the TRIUMF campaign will come from the leading groups: GANIL, IGFAE-USC, U. Regina and TRIUMF. GANIL will contribute with 3.5 mFTE (month Full Time Equivalent) in total: 1 senior researcher, 1 technician and two engineers. Personnel power from GANIL will be essential during the mounting, start up and running of the campaign. The IGFAE-USC will mobilise 2 senior researchers with: a full 1mFTE and 0.5mFTE for the other. The technician from the IGFAE-USC is expected to spend there 0.6mFTE while two students will be placed at TRIUMF for the full campaign during 2mFTE and the other one will dedicate 0.5mFTE. U. Regina is planning to contribute with a senior researcher with 1mFTE and 2 students that will spend 2mFTE in TRIUMF. Besides from TRIUMF, 1 senior with 1mFTE and 1 technician with 1mFTE are expected to participate to the mounting and measurements. The personnel power from TRIUMF will act as contact people and their involvement will be key for the success of the campaign.

For the rest of collaborators, it is difficult to estimate the number of scientists that will be involved in the mounting and data taking with ACTAR TPC at TRIUMF but a large majority of the collaboration members have shown their interest by signing the experiments and LoIs.

5.2 Financial resources

The capital investment for the experimental campaign at TRIUMF has been detailed in Table 1 and includes the cost of the shipping, the gas bottles for the experiments and the new upgrades of the setups.

The shipping of the detector amounts up to 38% of the total. The cost has been estimated based on a quotation provided by the ULISSE service from the CNRS. The budget includes the packing, which increases the price, as the field cage has to travel mounted inside the detector in order to avoid any vibration. Funds from GANIL, U. Regina and IGFAE-USC will cover the full cost with 30-50-20 sharing. The variety of experiments to be performed at TRIUMF requires the use of different gases as targets.

The collaboration will have to buy three bottles of pure H_2, D_2, and C_4H_{10} gas for the runs (total estimate ≃10 k€). As mentioned earlier, some parts of the detector will be upgraded in order to improve further the performance. The cost of the thick silicon detectors and the gas recycling system represents also a large amount of the total ≃ 22%.

Item	Amount (k€)	Laboratory in charge
Shipping detector to TRIUMF	70=21-35*-14	GANIL - U. Regina - IGFAE-USC
New gas recycling system	10+30*	GANIL
New array of silicon detectors	40*	IGFAE-USC
Electronics : preamplifiers	5*	GANIL-IGFAE-USC
Thick GEMS	4*	IGFAE-USC
Gaz Bottles : H_2, D_2, C_4H_{10}	10=5+5*	GANIL - U. Regina
Additional computer for DAQ	10*	IGFAE-USC
Operational costs	5	TRIUMF
TOTAL	184	

* Investment already done, or financing secured

Table 1: Secured capital costs for the ACTAR TPC campaign at TRIUMF.

The collaboration has already invested 65% of the capital needed for the campaign. The rest is partly secured by the different funding agencies of the collaboration partners. At this moment, there are ongoing discussions within the collaboration to decide the sharing of the remaining budget. The campaign of ACTAR TPC at TRIUMF relies primarily on the financial support of GANIL, the IGFAE-USC through the Spanish MINECO project PID2021-128487NB-I00 (PI B. Fernández-Domínguez) and U. Regina through a Discovery Grant (PI Grinyer) from the Natural Sciences and Engineering Research Council (NSERC) of Canada. The total budget for the experimental campaign including material and human resources is summarized in 2 with a detailed overview of the different contributions by laboratory. The capital investment of the total budget splits into 38-37-22 sharing for GANIL, IGFAE-USC and U. Regina. It is important to note that the upgrades of the setup will be used in future campaigns at GANIL.

6 Conclusions

To conclude, the ACTAR TPC collaboration has shown to be a successful collaboration. The campaign at TRIUMF will take advantage of the unique beam characteristics at the ISAC-II facility. The approved experiments will push the frontiers of knowlegde at the drip-lines, provide a better understanding of the nuclear matter at the extremes, search for new modes of decay, and constrain astrophysical reaction rates for HCNO breakout

Laboratory	Amount (k€)	%	Total personnel resources (mFTE)
GANIL	71	38	3.5
IGFAE-USC	68	37	4.6
U. Regina	40	22	3
TRIUMF	5	3	2
TOTAL	184	100	7.6

Table 2: Summary table of the capital investment and personnel resources for the TRIUMF campaign distributed per laboratory

in stars.

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