TRIUMF - EEC SUBMISSION EEC meeting: 202201S *Progress Report*		**Exp. No.** S2029 - *Deferred* **Date Submitted:** 2021-12-06 10:06:23

Title of Experiment:

Resonant proton elastic scattering on ^{17}F

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Safety Coordinator(s) for Group

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Beam Shift Requests:

16 shifts on: TUDA II (SEBT1)
Comment:

15 shifts 17F, 1 shift tuning

Beam Shifts Used:

Beam Shifts Remaining:

Basic Information:

Date submitted: 2021-12-06 10:06:23

Summary: This proposal aims to identify and measure the 2p decay branching ratio from the 6.15 MeV resonance in 18Ne. This measurement is important to resolve a major discrepancy in previous experiments and constrain the astrophysical 14O(alpha,p)17F reaction rate, an important break out reaction from the HCNO cycle.

Experimental Facility

ISAC Facility:

ISAC-II Facility: TUDA II (SEBT1)

Have all the Facility Coordinators and/or Collaboration spokespersons of the relevant experimental facilities been made aware of this proposal?: Yes

Secondary Beam

Isotope: 17F

Energy: 4.5 MeV/u

Optimal Intensity: 5000

Minimum Intensity: 500

Maximum Intensity: 50000

OLIS/ISAC: OLIS

Target/Source: Unknown

Energy Units: AMeV

Energy spread-maximum:

Time spread-maximum:

Angular Divergence:

Spot Size:

Charge Constraints: Fully stripped 9+

Beam Purity: Preferably 100% (9+)

Special Characteristics: A/q = 1.89

Safety Issues:

Presence of high voltage (5 - 10 kV) for the TPC and up to 200 V for the Si detectors.

Presence of gases (hydrogen and isobutane).

Resonant proton elastic scattering on ^{17}F

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Abstract

This proposal follows the Active Target and Time Projection Chamber (ACTAR TPC) letter of intent (S1931LOI) that was presented and endorsed by the EEC with high priority in 2019.

1 Scientific Value

Excited states in ^{18}Ne above the proton decay threshold (E_x = 5–10 MeV) play a key role in evaluating the ^{14}O(α,p)^{17}F reaction rate, an important break-out reaction from the HCNO cycle in explosive astrophysical scenarios. At typical novae outburst temperatures (0.1 to 0.4 GK), this reaction is dominated by a single resonance at 6.15 MeV [1, 2]. At higher temperatures (> 2 GK), additional resonances at 7.35 and 8.10 MeV begin to play a significant role [3]. While the energy and spin (1^-)

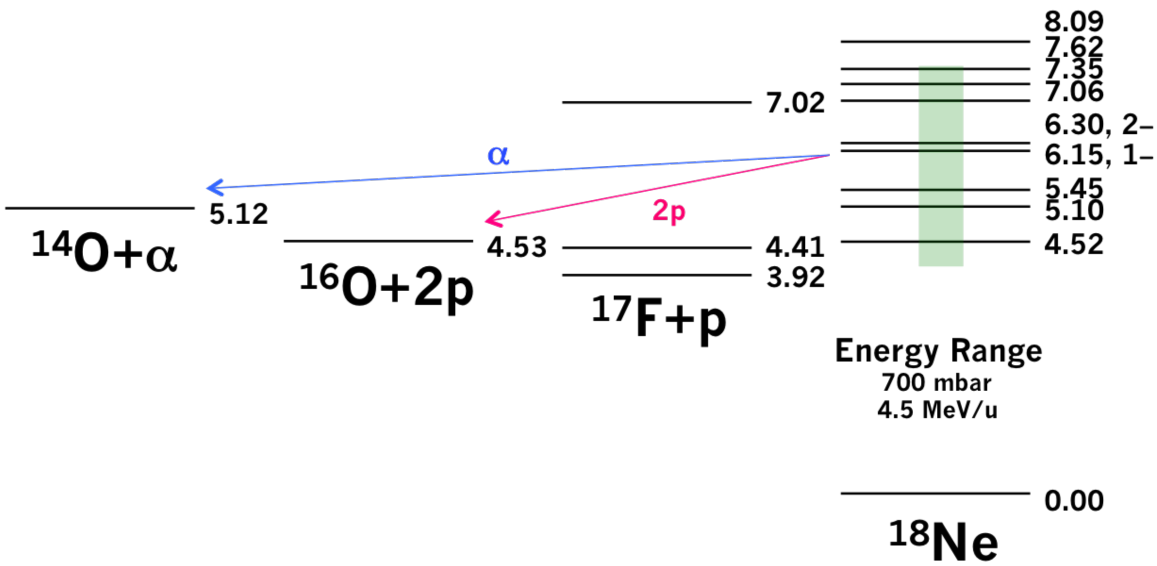

Figure 1: Decay level scheme and relevant resonances in ^{18}Ne. The green band represents the energy range that will be available for study in this proposal. One of the goals is to search for (or set limits) on the possible existence of a 2p-decay channel from the 6.15 MeV (1^-) resonance.

of the 6.15 MeV resonance are known, it is presently unclear whether this state decays by any mode other than single proton emission to the ground and first excited states of ^{17}F. The possible existence of an appreciable 2-proton decay branch has been identified but results are entirely inconsistent with each other (spanning 3 orders of magnitude) and no definitive conclusions can be drawn [4, 5, 6]. If a large 2p-decay branch could be confirmed, this would reduce the overall proton width and thus decrease the importance of this resonance for astrophysics. Using the largest 2p branch that has been reported [6], leads to a reduction in the ^{14}O(α,p)^{17}F reaction rate by 30% at novae temperatures [6].

The ^{18}Ne excited state and partial decay level scheme is presented in Fig. 1. Since there are no excited states known in ^{17}F between 4.41 and 7.02 MeV, sequential emission of two protons through an intermediate resonance can be ruled out. The ^{17}F resonance at 7.02 MeV is also far enough away and is not very broad (19 keV) thus interference from the tail of this resonance in the decay process (creating a type of sequential decay) is expected to be negligible. The decay must therefore proceed solely via simultaneous emission of two protons. If the 2p branch is large, this would be an ideal candidate to study correlations between protons that give insight into the nature of the 2p decay mechanism itself. These studies have been attempted using ground-state 2p emitters but, as these nuclei are located far very from stability and are produced in limited quantities, results have so far been limited to ^{45}Fe (75 total events) [7]. Additional insight into this rare decay mechanism must therefore rely on complementary studies using delayed charged particle decays (β2p) or 2p emission from unbound resonant states populated in reactions.

The 2p decay from the 6.15 MeV resonance has not been observed directly but rather inferred from data analysis by selecting events with multiplicity >1 and relying on kinematic signatures [4, 6, 8]. It is clear that proton decay to the ground and first excited states in ^{17}F dominate the decay of this resonance. Decay by α emission to ^{14}O has also never been measured. The total decay width of the 6.15 MeV resonance is $\sim$50 keV from the experiment of Ref. [4]. The 2p width was measured, in this same experiment, to be between 20-60 eV or Γ_{2p}/Γ_{tot} = 0.03% to 0.11% [4]. This corresponds to a partial cross section of about 4 mb compared to the 3660 mb for 1p decay from this resonance.

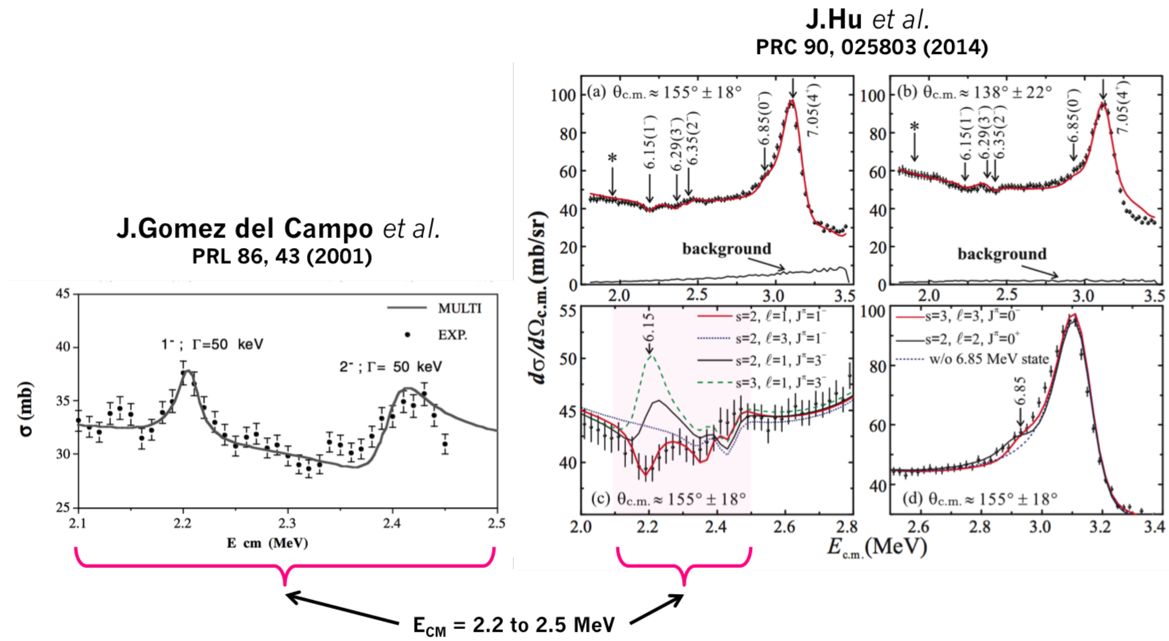

Figure 2: Spectral comparison between the experiments of Ref. [4] and Ref. [10] that used the same ^{17}F+p reaction to populate resonances in ^{18}Ne. The results of these experiments show a significant discrepancy in the peak shape of the 6.15 MeV resonance (highlighted region around $E_{CM} = 2.23$ MeV), the origin of which is still unclear.

Theoretically, this experimental result is not well understood since it is 1 to 2 orders of magnitude larger than the 0.03 to 0.2 mb values obtained in the calculations of Ref. [5]. It was proposed that the majority of "2p events" seen in Ref. [4] were most likely due to inelastic breakup of ^{17}F in the CH_2 target that was used in the experiment.

Additional uncertainties also exist in the 1p resonant elastic scattering data of Ref. [4]. The peak structure that was obtained in Ref. [4] for the 6.15 MeV resonance (see Fig. 2) is inconsistent with a 1^- spin/parity assignment. A 1^- should have resulted in a depletion of counts at the resonance energy. A reanalysis of these data by Ref. [9] suggests that the structure observed in Ref. [4] is more consistent with a 3^- assignment. As shown in Fig. 2, a recent measurement has now clearly shown the expected depletion of counts consistent with the 1^- assignment [10]. The 1^- spin/parity assignment has now been universally adopted in the astrophysical ^{14}O(α,p)^{17}F rate calculations. It is not entirely clear as to why these two data sets are incompatible and further investigation is warranted.

In a recent measurement using a ^{3}He beam, the authors of Ref. [6] populated resonances in ^{18}Ne using the ^{16}O(^{3}He,n) reaction. They observed an excess of counts where, based on kinematic arguments, one would expect to find 2p events from the decay of the 6.15 MeV resonance. They then used this excess to deduce an upper limit for the 2p branching ratio. Their result, $\Gamma_{2p}/\Gamma_{tot} < 27\%$, is 2 orders of magnitude larger than the upper limit deduced in Ref. [4] and 3 orders of magnitude larger than the theoretical estimate [5].

As shown in Fig. 1, an additional α decay channel from the 6.15 MeV resonance is also open, but has never been measured. Astrophysical reaction rate calculations instead rely on a measurement performed in the mirror nucleus ^{18}O. Although this branch is expected to be very small $\Gamma_\alpha/\Gamma_{tot} \sim 0.004\%$, the reaction rate scales linearly with this value. A change to the Γ_α value by 20% would cause the ^{14}O(α,p)^{17}F reaction rate to change by 20%. A direct measurement of this branching ratio is clearly desirable and can be performed as a by product of the proposed experiment.

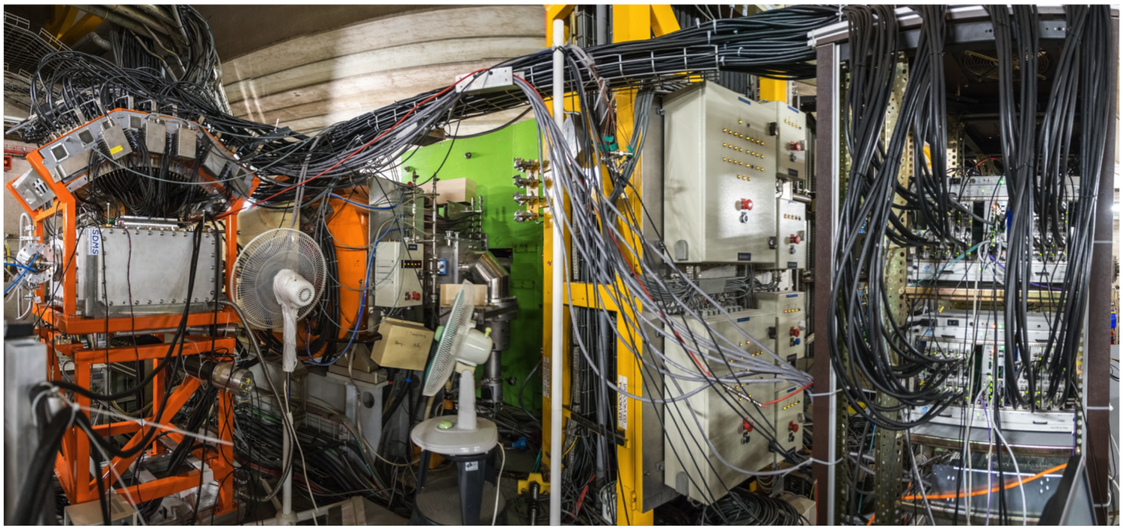

Figure 3: Photograph of ACTAR TPC and associated electronics installed at GANIL.

Evaluating the impact of a possible 2p decay branch from the 6.15 MeV resonance and its impact on the ^{14}O(α,p)^{17}F reaction rate requires unambiguous proof that this decay mode exists and an accurate measurement of its branching ratio. These are among the goals of the proposed experiment.

2 Description of the experiment

States in ^{18}Ne will be populated using the ^{17}F+p reaction, which is the same reaction used in Refs. [4, 10]. The ^{17}F beam will be produced at ISAC using 500 MeV protons from the TRIUMF main cyclotron impinging a silicon-carbide target coupled to a FEBIAD ion source at ISAC. The ^{17}F beam will then be accelerated through the RFQ, DTL and ISAC-II accelerator to an energy of 4.5 MeV/u and delivered to the active target and time projection chamber (ACTAR TPC).

3 Experimental equipment

The ACTAR TPC detection system was presented in a Letter of Intent (S1931 LoI) that was submitted to the last EEC meeting (summer 2019). The detector consists of a square pad plane with an active area of 25.6×25.6 cm^2 that is segmented into 16384 square pixels of 2×2 mm^2. The gas volume and a multi-layer downstream wall of Si detectors for particle identification (based on ΔE-E) are contained in an aluminum chamber that measures 60.6×60.6×33.5 cm^3. A detailed description is provided in Refs. [11, 12]. A photograph of the setup is shown in Fig. 3.

The detector operates on the basis of a time projection chamber. It is used to track, in three dimensions and on an event-by-event basis, particles that travel through the active region. The amount of charge per unit length as well as the total length of the tracks is related to both the charge and mass of the individual particles, which is crucial for particle identification. In 2018, an ^{18}O+p resonant elastic scattering experiment was performed with ACTAR TPC at GANIL, which is similar to the ^{17}F+p reaction proposed here. A sample spectrum obtained from the ^{18}O+p experiment is shown in Fig. 4. The resolution on the reconstructed excitation energies of ^{19}F resonances obtained from the (p,p) and (p,α) channels were 38(3) keV and 54(9) keV (FWHM), respectively [13]. A sample event shown in 2 and 3 dimensions is presented in Fig. 5 for ^{18}O beam on ^{12}C (isobutane

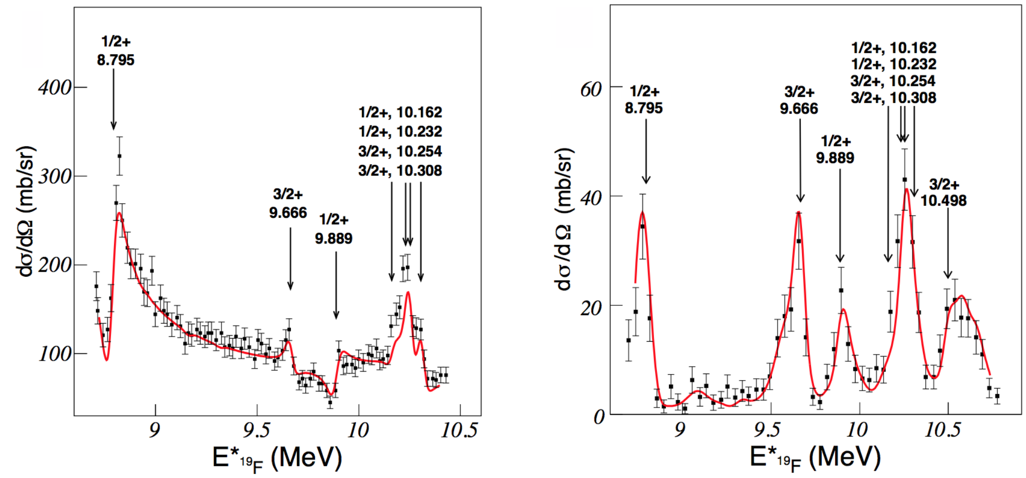

Figure 4: Excitation energy of ^{19}F deduced from the (p,p) (left) and (p,α) (right) channels at centre-of-mass angles $\theta_{cm} = (160\pm5)^{\circ}$. The energy resolutions obtained from these two channels were 38(3) keV and 54(9) keV FWHM, respectively [13].

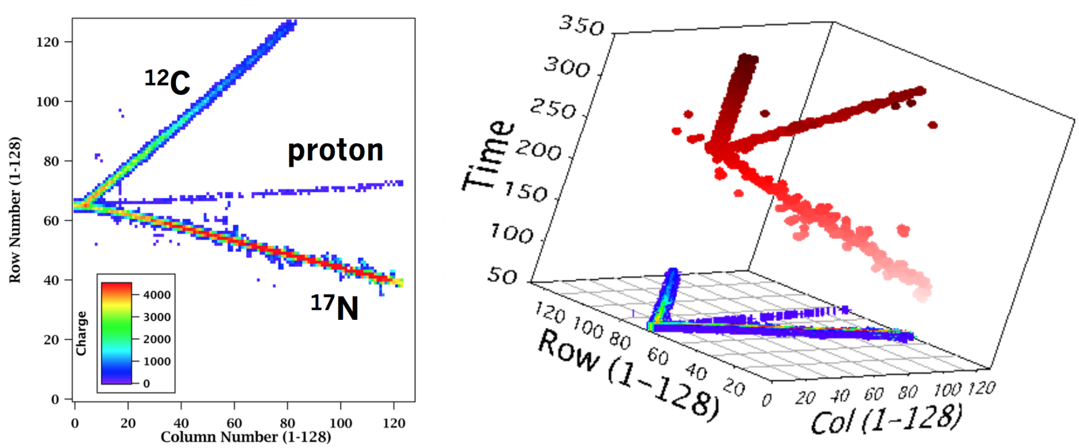

Figure 5: Sample ^{18}O+^{12}C $\rightarrow$ ^{17}N+p event in (left) 2 dimensions (charge collected on the pixels) and (right) 3 dimensions (reconstructed with timing information).

gas target) leading to ^{17}N+p. In the proposed experiment at ISAC, we will be searching for the simultaneous detection of an ^{16}O recoil plus 2 proton tracks that share the same reaction vertex and occur in a very specific region of the detector that corresponds to the excitation energy of the 6.15 MeV resonance.

The detector will be operated with a gas mixture of H_2(95%)+iC_4H_{10}(5%) at a total pressure of 700 mbar. When the beam enters the gas volume, ^{17}F beam ions will continuously lose energy along their trajectories, allowing several resonances to be populated. With a single beam energy, a large range of excitation energies in ^{18}Ne can be accessed simultaneously, which is a major advantage of thick-target experiments. With the gas mixture and pressure described above, the energy range that will be scanned with an incident beam of ^{17}F at 3.45 MeV/u (energy at the start of the active region) is indicated by the green band in Fig. 1. This corresponds to all of the relevant resonances in ^{18}Ne up to centre-of-mass energies of 3.4 MeV or ^{18}Ne excitation energies between 3.9 MeV (the proton separation threshold) and 7.3 MeV. The 6.15 MeV resonance will be populated 11.4 cm into

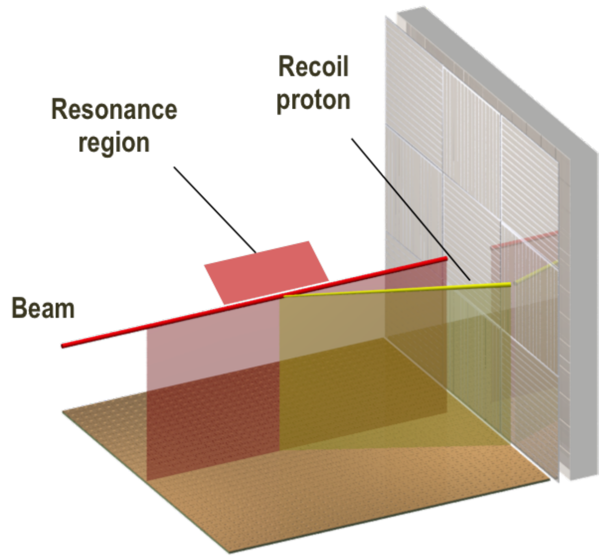

Figure 6: Schematic representation of resonant proton elastic scattering in an active target. Beam enters the detector from the left and loses energy as it traverses the gas volume. At a particular location in depth, the beam energy corresponds to the energy of the particular resonance of interest, the “resonance region”. If the resonance state is populated it will emit (primarily) protons from this location. Resonance energies are therefore correlated to position along the beam axis.

the active volume (nearly centered in the 25.6 cm active region) and this is where, in the detector, we would expect to see 2-proton emission. A schematic of the detection principle is shown in Fig. 6.

Unreacted ^{17}F beam (and any beam contaminants) will be stopped in a beam dump that will be located inside the active target detector just after the active region. The beam dump is part of the ACTAR TPC detection system. As shown in the schematic of Fig. 6, a downstream wall of Si and CsI detectors will be used to detect high energy protons emitted at forward lab angles from the dominant elastic ^{17}F(p,p) and inelastic ^{17}F(p,p$'$) proton channels.

The ACTAR TPC electronics and data acquisition are described in Refs. [13, 14]. The entire setup (see Fig. 3) will be transported from the GANIL laboratory in France to TRIUMF. This includes all of the computers (data acquisition and systems control/command) as well as its own secure and protected data storage system that connects to the setup via a series of Ethernet cables. In terms of overall data rate and disk space, we typically write 10 Tb of data per day when operating at a trigger rate of 100 Hz. We would write these data on our own server, which will be backed up on a secure server in Lyon, France.

4 Readiness

The ACTAR TPC detector has been fully operational since 2017 and has been successfully used in several experiments at GANIL. Most recently, we have used this detector to discover proton emission from a short-lived ($T_{1/2}$ = 155 ns) isomeric state in ^{54}Ni. Results were published earlier this year in Nature Communications [15] and a sample of the data are shown in Fig. 7. In this figure, only a fraction of the total statistics are presented to show the feasibility for performing experiments with limited statistics. As this figure clearly shows, measuring the proton energies from $^{54\mathrm{m}}$Ni decay is feasible with only ∼20 counts in each peak. Discovery that this decay mode exists, and determining

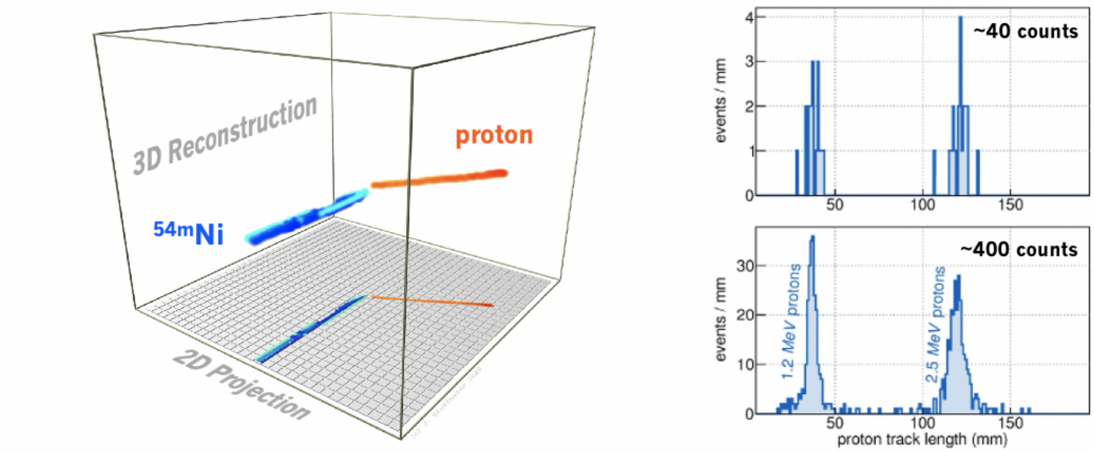

Figure 7: Experimental data from ACTAR TPC obtained from an experiment that identified proton emission from a short-lived isomeric state in ^{54}Ni from Ref. [15]. The image on the left is a single event that has been fully reconstructed in three dimensions. On the right, the proton energies are determined based on the length of their tracks in the TPC. Both plots are identical but show different statistical yields. The top plot has ∼20 counts in each peak (40 counts total) which is clearly sufficient to provide an accurate measure of the energies.

the branching ratio, requires even less. We have also recently submitted a new article to Nature on the discovery of a low energy proton-emitting isomer in ^{53}Co [16]. In this experiment, the branching ratio $b_p = 0.025(4)\%$ was deduced from a total of 72 events.

The entire system is fully tested and experiment ready and we only need to organize the packing, shipping and installation of the detector at TRIUMF. A campaign of ACTAR TPC experiments at TRIUMF would also have to be coordinated with the GANIL beam schedule as our intention is to perform experiments at TRIUMF during GANIL extended shutdowns.

5 Beam time required

Beams of ^{17}F have previously been demonstrated at ISAC, with yield measurements as high as nearly 10^6 ions/s (at the yield station). This was achieved using a SiC production target coupled to a FEBIAD ion source. Assuming a factor of 10 loss through the post acceleration phase, a maximum intensity of 10^5 ions/s should be feasible at the target position in the ISAC-II experimental hall. As described below, our experiment can be performed with only 5000 ions/s.

The stable isobaric contaminant, ^{17}O, is a concern for this experiment because it will be produced at much higher intensity than ^{17}F. The mass difference between these two isobars is 1 part in 5700, which is just below the Δm/m = 1/2500 resolving power of the mass separator. The beam delivery group estimates a ratio of ^{17}O/^{17}F = 100. Since the overall ^{17}F production yield is many orders of magnitude higher than we require, one option would be to run fully stripped ^{17}F^{9+}, which would completely eliminate the ^{17}O contaminant. The beam delivery group estimates that 5000 ions/s of fully stripped ^{17}F^{9+} delivered to the experiment is feasible. The A/q for this beam would be 17/9 or 1.89, which < 2, so we may need to consider accelerating the 8+ charge state and using a stripper foil before the dipole leading to the SEBT1 beam line at ISAC-II. This may reduce the ^{17}F intensity further or allow some of the ^{17}O to reach the experiment. As described below, the experiment will still be feasible with less intensity and with some (up to $\sim 10^4$ pps) beam contamination.

Table 1: Count rate estimates for 2p and α decay from the 6.15 MeV resonance.

Γ_{2p}/Γ_{tot} (%)	2p yield (counts/day)	$\Gamma_{\alpha}/\Gamma_{tot}$ (%)	α yield (counts/day)	Reference
< 27.0	< 7×10^4	0.004	10	[6]
0.03 to 0.11	70 to 280			[4]
0.001 to 0.006	2 to 14			[5]

To ensure good resolution and maintain efficient beam tracking, the active target must be operated at a total beam intensity of 5×10^4 ions/s or less. Above this rate, we quickly lose efficiency, resolution, particle identification and beam tracking capabilities. Increased pile up at higher rates will further degrade the performance of the detector. If 5000 ions/s of pure $^{17}F^{9+}$ beam can be delivered then we are well below the limiting rate of the detector.

The number of 2p-decay and α-decay events from the 6.15 MeV resonance per day is provided in Table 1 based on the known cross section to populate the state at 6.15 MeV resonance [10] and assuming a ^{17}F beam intensity of 5000 ions/s. Because of the large discrepancy between the literature results for the 2p-decay channel, all options are provided for comparison. These include (i) the upper limit of 27% deduced in Ref. [6], (ii) the range of values obtained in Ref. [4], and (iii) the theoretical range that was predicted in Ref. [5]. For the α-decay channel, a width of 2 eV (0.004%) is assumed as this is the value adopted from the ^{18}O mirror and used in astrophysical rate calculations.

One of the goals of the present experiment is to observe (or set strict limits on) the possible 2p-decay of the 6.15 MeV resonance. From the count rate estimates presented in Table 1, the 2p channel would be clearly observed in 5 days of beam time even with the lowest possible experimental limit of 70 counts/day from Ref. [4] as this would give 350 total events. Direct observation will also be feasible even if the lower theoretical limit (2 counts/day or 10 total counts in 5 days) is correct. Even a null observation after 5 days is still a very important result because it would conclusively rule out this decay mode as being relevant to the $^{14}O(\alpha,p)^{17}F$ astrophysical reaction rate.

As a by product, direct observation of the α channel will also be feasible with an expected detection rate of 10 counts/day (or 50 total after 5 days of beam time). A direct measurement of this branch would be extremely valuable to confirm the inputs used in the present astrophysical rate calculations. This measurement will be performed simultaneously with the 2p-decay measurement described above. No additional beam time is required.

Based on the count rate estimates in Table 1, the absolute minimum intensity required by the experiment would be 10 times less or 500 ions/s. The maximum intensity would be 10 times more than requested, 5×10^4 ions/s, which is the rate limit imposed by the detector.

We therefore request a total of **16 shifts** of pure $^{17}F^{9+}$ beam from ISAC-II with a nominal beam intensity of 5000 ions/s. This includes 15 shifts for performing the actual experiment and 1 additional shift for beam tuning to the experimental area.

6 Data analysis

Data analysis will be performed using the software developed by the ACTAR TPC collaboration and used in previous experiments with this detector.

7 Response to the 2020 EEC report

This proposal was presented previously at the EEC meeting in January 2020. It was given "deferred" status because of concerns about the result from Ref. [4] that the committee concluded was an "unphysical value for the cross section, which erroneously appeared in the literature". As described at that time, and again in this proposal, we are aware of the fact that the results of Ref. [4] should be treated with some degree skepticism, but their reported cross section is certainly not "erroneous". In Fig. 2 of their paper, they observed more than 100 counts in the 2p channel that only appeared when the beam energy was above the energy threshold for populating this resonance. The cross section they obtained is likely due to a combination of 2p decay from the 6.15 MeV resonance with ^{17}F break up in the target that was misidentified because their detection system was unable to distinguish between the two. This possibility was described in Ref. [5].

However, this was also not the only experiment to observe such a high yield. In Ref. [6], using a completely different reaction, the authors proposed an even higher branching ratio for 2p decay from this resonance. Because of similar limitations, they could also not conclusively identify the 2p channel directly but inferred it based on known kinematics and the expected response of their setup.

These two measurements are still, to this day, the only experimental data that are available on this decay channel. For the α channel there are no experimental data. In terms of rate estimates, the committee reported that "The count rates in the proposal were significantly overestimated due to the use of an unphysical value for the elastic cross section". However, at no time (past submission or present proposal) were the absolute values from either of these experiments relied upon to determine the feasibility of the experiment. They were used only to define a range of possible rates because these are the only data we have. For overall feasibility, we have based our decision to propose this experiment on the theoretical lower limit of 2 to 14 events per day (see Table 1). In 5 days, we would accumulate between 10 and 70 events, which is more than sufficient to unambiguously observe the 2p channel in the active target and measure its branching ratio (based on previous experiments described above and demonstrated in Fig. 7). For the α-decay channel, 10 counts per day (50 total) is also sufficient to provide a first measurement of its branching ratio. If there were more beam available, and our estimates are conservative, then these numbers will increase.

The active target will provide, by far, the most convincing experimental data that will be able to unambiguously resolve the discrepancy between these past measurements and theory. It will provide first measurements of the 2p and α-decay branching ratios and thus be able determine the relevance of these decay modes in the ^{14}O(α,p)^{17}F reaction rate. Beams of ^{17}F are not available at GANIL, so this is a unique opportunity for ACTAR TPC at TRIUMF. And the fact that older measurements may have provided "erroneous" data should only strengthen the motivation of the present proposal.

This experiment, and the ACTAR TPC at TRIUMF campaign that was previously endorsed with high priority by the EEC, is the first step towards building a dedicated active target for TRIUMF. The Exotic Nuclei Active Target Time Projection Chamber (EXACT-TPC) was fully supported by the TRIUMF PPAC in 2021.

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