TRIUMF - EEC SUBMISSION		Exp. No.
EEC meeting: 201607S	TRIUMF	S1692 - *Approved*
Original Proposal		**Date Submitted:** 2016-06-20 07:44:21

Title of Experiment:

Breakout reactions from the pp-chain and the νp-process: Measurement of the $^{7}Be(\alpha,\gamma)\,^{11}C$ reaction rate in inverse kinematics

Spokesperson(s) for Group

A.A. Chen, A. Psaltis

Safety Coordinator(s) for Group

C. Ruiz

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D.A. Hutcheon	TRIUMF	Professor Emeritus
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Beam Shift Requests:

2 shifts on: DRAGON (HEBT2)
Comment:

^{12}C beam from OLIS

4 shifts on: DRAGON (HEBT2)
Comment:

^{6}Li beam from OLIS

4 shifts on: DRAGON (HEBT2)
Comment:

^{7}Li beam from OLIS

32 shifts on: DRAGON (HEBT2)
Comment:

^{7}Be beam using the Tantalum target.

Basic Information:

Date submitted: 2016-06-20 07:44:21

Summary: The production of the light p-nuclei can be described by the νp-process. It has been recently shown that the 7-Be(alpha,gamma)11-C reaction can significantly influence this production. Nevertheless, this reaction has not been studied well yet in the relevant temperature range. The purpose of this proposal is the first study of important resonances of 7-Be(alpha,gamma)11-C reaction with unknown strengths using DRAGON.

Samples List:

Experimental Facility

ISAC Facility:

ISAC-I Facility: DRAGON (HEBT2)

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

Secondary Beam

Isotope: 12C

Energy: 162-198

Intensity Requested: 1E10

Minimum Intensity: 1E09

Maximum Intensity: 1E12

OLIS: Yes

ISAC Target: No

Isotope: 7Li

Energy: 412-550

Intensity Requested: 1E10

Minimum Intensity: 1E09

Maximum Intensity: 1E12

OLIS: Yes

ISAC Target: No

Isotope: 6Li

Energy: 250-330

Intensity Requested: 1E10

Minimum Intensity: 1E09

Maximum Intensity: 1E12

OLIS: Yes

ISAC Target: No

Isotope: 7Be

Energy: 412-550

Intensity Requested: 1E07

Minimum Intensity: 5E06

Maximum Intensity: none

OLIS: No

ISAC Target: Yes

Energy Units: AkeV

Energy spread-maximum: best

Time spread-maximum: consistent with best energy spread

Angular Divergence:

Spot Size: 2

Charge Constraints:

Beam Purity:

Special Characteristics:

Beam Delivery Information

Target Material(s):

Comments:

Beam Readiness Review Comments:

- DRADON experiment at ISAC-I (A.A. Chen, A. Psaltis)

- Requested: ^{7}Be $5*10^{6}$ and ^{6}Li, ^{7}Li, ^{12}C beams at $1*10^{9}$
- Comments: all beams possible, but separate safety required
- Experiment is evaluated as feasible.

Experiment Support

Beam Diagnostics Required:

Standard DRAGON diagnostics

Signals for Beam Tuning:

Provided by DRAGON group

DAQ Support:

Standard DRAGON DAQ

TRIUMF Support:

Standard DRAGON manpower and resources. Provision of ^{7}Be and OLIS beams.

Other Funding:

NSERC grant of McMaster group; additional resources (manpower) from collaborators

Summary of possible hazards associated with the experimental apparatus, precautions to be taken, and other matters that should be brought to the notice of the Safety Officer.:

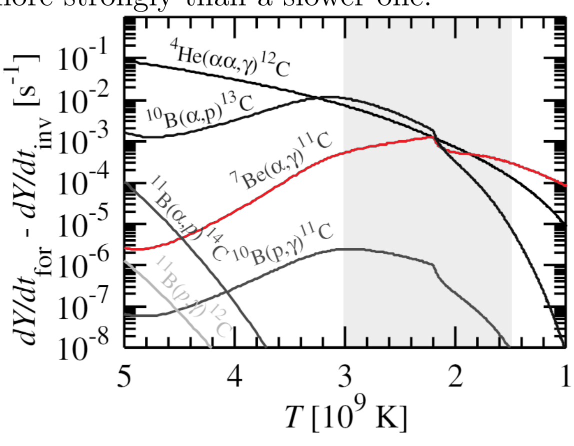
This experiment does not introduce any additional safety hazards beyond those covered under the normal operation of the DRAGON and ISAC facilities. Safety procedures for the operation of DRAGON have been developed and approved.

1 Scientific Motivation

The origin of the 35 neutron-deficient stable isotopes with mass numbers $A \geq 74$ - between ^{74}Se and ^{196}Hg - in the proton-rich side of the valley of stability, known as "p-nuclei", has been a long-standing puzzle in nuclear astrophysics [1, 2]. The solar abundances of p-nuclei are 1-2 orders of magnitude lower compared with the respective r- and s-nuclides in the same mass region [3]. The photodisintegration of pre-existing neutron-rich isotopes, the γ-process [4], which is to date the most promising nucleosynthetic scenario of the p-nuclides and takes place in the oxygen-neon layer of core-collapse supernovae, still cannot reproduce the abundances of the light ^{92,94}Mo and ^{96,98}Ru isotopes, as well as the rare species ^{113}In, ^{115}Sn and ^{138}La.

The recently proposed νp-process [5–7] has considerably alleviated this problem. It is thought to occur in core-collapse supernovae when intense neutrino fluxes create proton-rich ejecta. Antineutrino absorptions on free protons in the proton-rich environment create neutrons that are captured immediately by neutron-deficient nuclides, thus bypassing the rp-process waiting-point nuclei near A $\sim$ 60-70, and enabling the reaction flow to reach even heavier nuclei. It has been shown that the νp-process (T_9=1-3), could fill the solar abundance of ^{92,94}Mo, ^{96,98}Ru that are underproduced in other proposed models [7]. Nevertheless, it is important to stress that the νp-process is very sensitive in both supernova dynamics and nuclear physics. As a consequence, the impact of these two factors in the final abundances of p- nuclei is actively being explored by several groups, dating back to when the νp-process was first proposed in 2006 [5–7].

In a recent study, Wanajo *et al.* [8] focused on the nuclear physics uncertainties of the νp-process. One of their important conclusions is that breakout from the pp-chains through the ^{7}Be$(\alpha,\gamma)^{11}$C reaction affects the proton-to-seed ratio at the beginning of the νp-process, resulting in a significant influence on the production of the light p-nuclei in the A $\sim 100-110$ region. Furthermore, in the late phase of the νp-process, $T_9 \lesssim 2$, ^{7}Be$(\alpha,\gamma)^{11}$C competes favorably with the triple-α process (Figure 1 - Left). A larger rate during this phase leads to increased production of intermediate-mass nuclei that remove protons from the environment, acting as proton "poisons" [8]. The p-process abundances were calculated for variations in the ^{7}Be$(\alpha,\gamma)^{11}$C rate [9] by up to a factor of 10 (up and down). While the abundance variations were not tabulated, the right panel of Figure 1 (adopted from [8]) illustrates the sizes of these variations. In particular, it was found that a faster rate affects the abundances more strongly than a slower one.



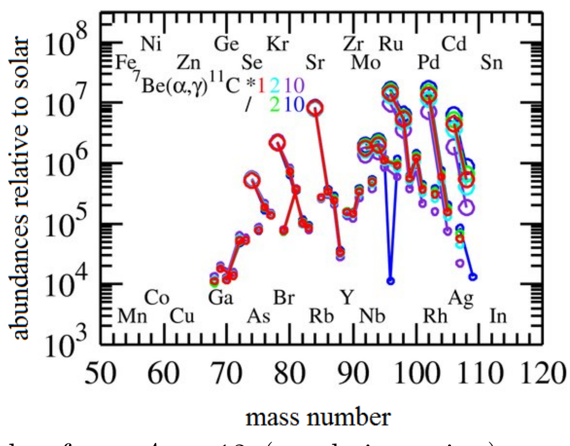


Figure 1: Nuclear flows for the reactions that bridge from $A < 12$ (pp-chain region) to $A \geq 12$ (CNO-region) as a function of temperature. The band indicates the temperature range relevant to the νp-process ($T_9 = 1.5 - 3$) and the red line shows the ^{7}Be$(\alpha,\gamma)^{11}$C reaction. (Right) Abundances of isotopes relative to solar values for different rates of the ^{7}Be$(\alpha,\gamma)^{11}$C reaction. The color coding corresponds to different values of the rate as indicated in the inset. Both figures are adopted from [8].

In addition to the above, the $^7\mathrm{Be}(\alpha,\gamma)^{11}\mathrm{C}$ reaction has been long considered to play a major role as the breakout reaction of the hot *pp*-chain, which takes place in low-metallicity massive stars or novae [10]. There are four reaction sequences that include $^7\mathrm{Be}(\alpha,\gamma)^{11}\mathrm{C}$ in the hot *pp*-chain or *rap*-process, the first:

$$^7\mathrm{Be}(\alpha,\gamma)^{11}\mathrm{C}(\beta^+,\nu)^{11}\mathrm{B}(p,2\alpha)^4\mathrm{He}$$

is called *pp*-V and takes place in high-temperature environments, whereas the rest are the breakout processes, known as rap II,III and IV respectively:

$$^7\mathrm{Be}(\alpha,\gamma)^{11}\mathrm{C}(p,\gamma)^{12}\mathrm{N}(\beta^+,\nu)^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}(p,\gamma)^{14}\mathrm{O}$$
$$^7\mathrm{Be}(\alpha,\gamma)^{11}\mathrm{C}(p,\gamma)^{12}\mathrm{N}(p,\gamma)^{13}\mathrm{O}(\beta^+,\nu)^{13}\mathrm{N}(p,\gamma)^{14}\mathrm{O}$$
$$^7\mathrm{Be}(\alpha,\gamma)^{11}\mathrm{C}(\alpha,p)^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$$

The aforementioned reaction sequences control significantly the production of heavy nuclides, since the nucleosynthesis in the early epoch of core collapse supernovae first produce the seed nuclei from the *pp*-chain region in the *r*-process and the νp-process [5–7, 11]. The hot *pp*-chain bypasses the triple-α process and creates CNO nuclei. Beyond that, these reactions can possible play an important role in nucleosynthesis in other astrophysical sites, such as novae or even in Big Bang Nucleosynthesis [12, 13].

However, most of the reactions related to breakout processes have not yet been studied well, since they involve unstable nuclei. Almost all α- induced cross sections and reaction rates are estimated using statistical models, despite the fact that they are not precise enough in the region of light masses [10]. For $^7\mathrm{Be}(\alpha,\gamma)^{11}\mathrm{C}$ a calculation of the reaction rate has been performed by our group using the latest version of TALYS reaction code (v1.8) [14] and is compared with the rate from the updated NACRE II evaluation for nuclei with mass number A$<$ 16 [15] (Figure 2). The latter includes experimental information on the two lowest resonances (described in Section 2). A large difference between these rates is seen in the low temperature regime. Also shown is the reaction rate evaluation of Caughlan and Fowler [9], which follows the TALYS trend for the lower temperatures. At high, astrophysically relevant, temperatures the Hauser-Feshbach model used by TALYS seems to be more reliable [13]; here, however, contributions from higher-lying resonances can significantly affect the reaction rate. As shown in the right panel of Figure 2, in the temperature region relevant to the νp-process discrepancies between the TALYS and NACRE II rates reach up to a factor of 5.

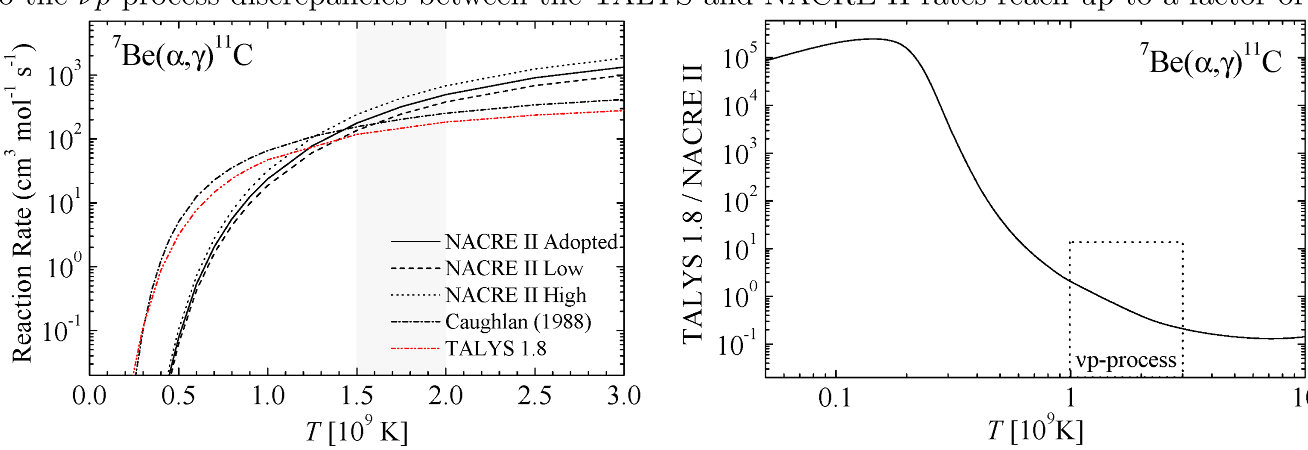


Figure 2: (Left) Reaction rates for the $^7\mathrm{Be}(\alpha,\gamma)^{11}\mathrm{C}$ using NACRE II, TALYS 1.8 and the Caughlan/Fowler compilation [8, 14, 15]. The temperature range where it competes with triple-α process is indicated with the gray rectangle. (Right) Comparison between TALYS 1.8 and NACRE II reaction rates. The temperature range relevant to the νp-process is indicated.

Experimental efforts towards the direction of measuring reaction rates related to breakout processes, such as the ^{7}Be$(\alpha,\gamma)^{11}$C, are very important and pose a challenge for Nuclear Astrophysics for the following years. Therefore, in the following we propose to perform the first measurement of the ^{7}Be$(\alpha,\gamma)^{11}$C reaction in inverse kinematics using the DRAGON recoil separator.

2 Previous work related to the ^{7}Be$(\alpha,\gamma)^{11}$C reaction

There are four resonances of the ^{7}Be $+\ \alpha$ system that are expected to regulate the reaction rate in the temperature range $T_9 \sim 1.5$-3. The first two levels above the α-threshold that determine the reaction rate at temperatures $T_9 = 0.5$-1 were first studied by a direct approach, using a radioactive ^{7}Be target by Hardie *et al.* [16]. Their spectroscopic properties are presented below:

- **E_x= 8105 keV** (E_r= 560 keV): this state has $J^\pi = 3/2^-$ and an energy uncertainty of ±17 keV. The alpha-width measured by Hardie *et al.* [16] has a value of 6^{+12}_{-2} eV and the gamma-width is 0.350 ± 0.056 eV. A calculated alpha width using the α-structure amplitudes of Kurath [17] gives a value of 53 eV.

- **E_x= 8421 keV** (E_r= 877 keV): the energy of this level is known to $\pm$ 2 keV, and has spin/parity $J^\pi = 5/2^-$. The gamma-width Γ_γ has been measured to be 3.1 ± 1.3 eV; the alpha-width Γ_α has an experimental value of 12.6 ± 3.8 eV [16] and a calculated one of 11 eV [17].

The next two levels could contribute to the rate at higher temperatures, namely T_9= 1.5-3, and therefore significantly change important nuclear physics parameters in the νp-process [8]. These states were studied by Wiescher *et al.* [18] via the ^{10}B(p,γ) reaction but their resonance strengths still remain unknown:

- **E_x= 8654 keV** (E_r= 1110 keV): the spin/parity of this level is $J^\pi = 7/2^+$ and its energy is known $\pm$ 4 keV. The total width of this state is $\Gamma_{tot} \leq 5$ keV, and $\Gamma_\gamma/\Gamma_{tot} < 0.06$ [18] .

- **E_x= 8699 keV** (E_r= 1155 keV): this level has $J^\pi = 5/2^+$ and an energy uncertainty of $\pm$ 2 keV. It is a broad state with a total width of Γ_{tot}= 15 $\pm$ 1 keV, and $\Gamma_\gamma/\Gamma_{tot}$= $(2.6 \pm 0.15) \times 10^{-4}$ [18]

E_x (keV)	E_r (keV)	J^π	Γ_α (eV)	Γ_γ (eV)	$\omega\gamma$ (eV)
8104.7(17)	560(17)	$3/2^-$	6^{+12}_{-2}	0.350 ± 0.056	0.331
8420(2)	877(2)	$5/2^-$	12.6 ± 3.8	3.1 ± 1.3	3.80
8654(4)	1110(4)	$7/2^+$	$\leqslant 5$ keV	-	-
8699(2)	1155(2)	$5/2^+$	15 ± 1 keV	-	-
8900	1356	$(9/2^+)$ or $3/2^+$	8 keV	-	-

Table 1: Resonance parameters adopted for the ^{7}Be$(\alpha,\gamma)^{11}$C reaction, Q-value=7543.62 keV. Experimentally measured resonance strengths are adopted from [21], and for E_x=8900 keV from [19].

In addition, Yamaguchi *et al.* [19] have recently studied the ^{7}Be$(\alpha, p)^{10}$B stellar reaction via elastic and inelactic scattering of ^{7}Be$+\alpha$ in a series of experiments at the CRIB facility. A new resonance at 8.90 MeV, with possible spin-parity $(9/2^+)$ or $3/2^+$, was discovered and it is expected to enhance the total reaction rate of ^{7}Be$(\alpha,\gamma)^{11}$C by 10%, compared with NACRE-II [15] at the key temperature region for the $\nu p-$process [8]. Hence, an exploratory experimental investigation of this resonance with DRAGON would be helpful [10].

Lastly, an interesting feature of the ^{7}Be + α system worth mentioning is the nuclear cluster structure of ^{11}C, consisting of two α particles and a ^{3}He weakly interacting at the level E_x= 8421 keV [19]. The cluster was studied by Descouvemont [20] using the three-cluster Generator Coordinate Method.

The currently established level structure of ^{11}C, along with its mirror nucleus ^{11}B is presented in Figure 3, and all spectroscopic properties of the key levels above the α threshold are shown in Table 1.

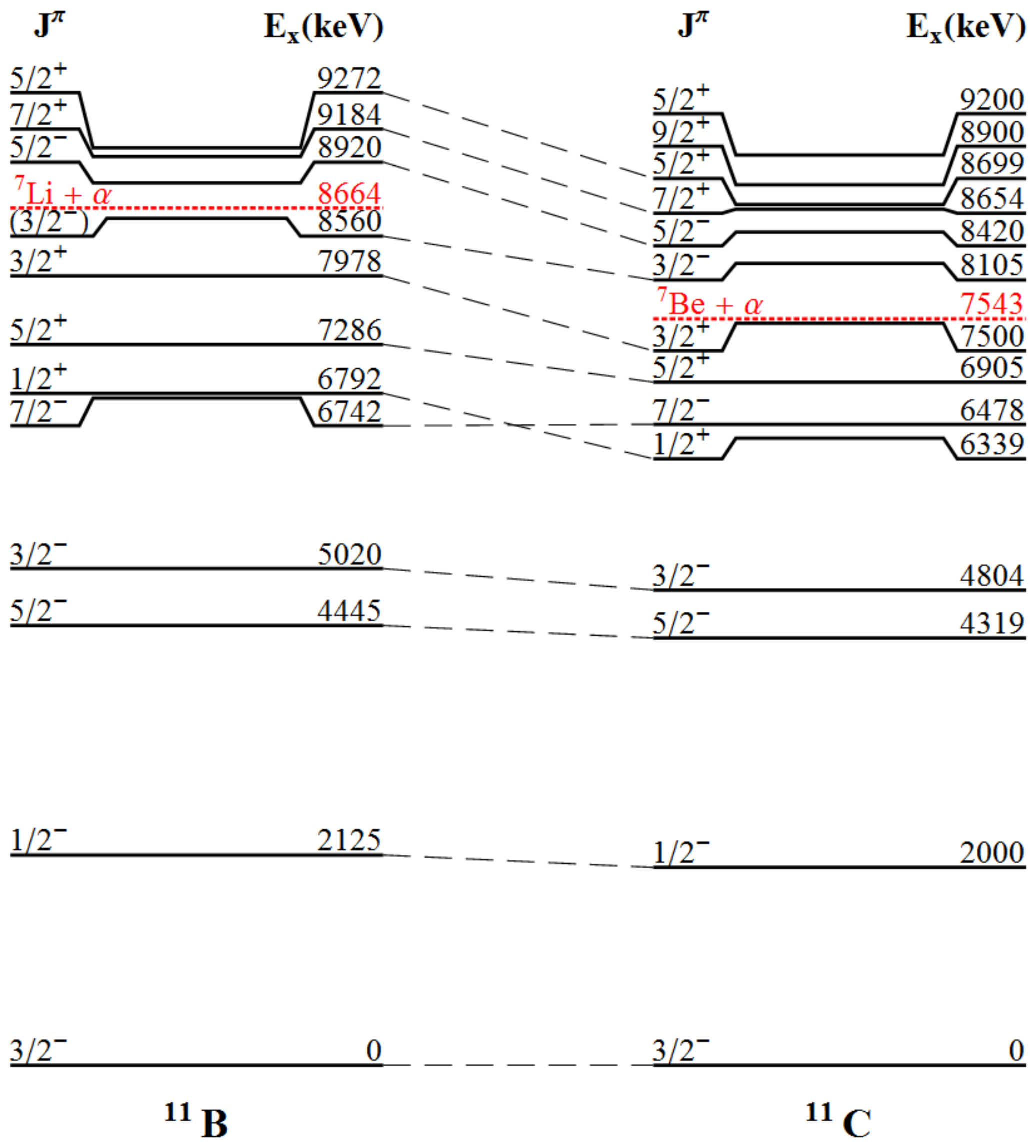


Figure 3: Level structure of ^{11}C close to the ^{7}Be$+\alpha$ region and the the analog state region for the mirror nucleus ^{11}B. Data retrieved from [22].

3 Description of the Experiment

We propose to study the ^{7}Be$(\alpha,\gamma)^{11}$C reaction using a ^{7}Be beam in inverse kinematics with the DRAGON recoil separator. For a more detailed description about the DRAGON facility the reader is referred to Refs. [23, 24]. A schematic representation of the facility is shown in Figure 4. The objectives of this experiment are multiple:

1. make the first direct measurements of the 1110-keV and 1155-keV resonances, attempt to measure their to date unknown strengths and at least set a meaningful upper limit and

2. attempt an exploratory measurement of the newly discovered resonance at 1356-keV [19] to see if the resonance can be located and if the strength can be at least constrained.

All these measurements will be inside the Gamow window for T_9 =1.5-3, corresponding to E_r= 0.240-1.420 keV. The projected ^{7}Be beam intensity at ISAC is 1×10^7 particles per second [25] (more on Section 5). Studying the ^{7}Be$(\alpha,\gamma)^{11}$C reaction poses a great challenge for DRAGON in the sense of testing its acceptance in the light mass regime. The maximum momentum cone of the reaction exceeds DRAGON's acceptance, which is around ±21 mrad [23] - 43.3 mrad for the 1110-keV, 42.7 mrad for the 1155-keV resonance - and some events are expected to be lost, posing an issue for the transmission of the recoils. For this reason, a Monte Carlo simulation of DRAGON using GEANT3 [26] was performed to investigate the transmission efficiency of the recoils in the separator, along with the BGO array efficiency.

The ^{7}Be$(\alpha,\gamma)^{11}$C reaction was simulated using the GEANT3 toolkit of DRAGON [26]. All important data regarding ^{11}C recoils, such as energy levels, lifetimes and branching ratios were adopted from Ref. [21]. For the first two resonances above the α-threshold, namely E_x= 8105 keV (E_r= 560 keV) and E_x= 8420 keV (E_r= 877 keV), kinematics are especially unfavourable for DRAGON, there are no known experimental angular distributions for these decays and the transmission is limited to ~ 5 %. Thus we propose to to use ^{6}Li(α,γ) reaction as a benchmark for our measurements. Using known branching ratios and angular distributions from Ref. [27] our GEANT simulations have shown that the E_x= 5164 keV state (E_r= 703 keV) of ^{10}B has maximum momentum cone angle of 30 mrad and resulted into $\sim 60\%$ recoil transmission. For the rest of the ^{11}C resonances:

- **E_x= 8654 keV** (E_r= 1110 keV): branching ratios are unknown for this state and therefore the corresponding ones from the mirror state of ^{11}B were used [21] (E_x= 9184 keV). The recoil transmission was 27% after 500-5000 events simulations.

- **E_x= 8699 keV** (E_r= 1155 keV): the branching ratios for this state are already known from Hardie *et al.* [16]. The recoil transmission was 18% after 500-5000 events simulations.

- **E_x= 8900 keV** (E_r= 1356 keV): for this state and its mirror state of ^{11}B branching ratios are unknown, and therefore simulations are not reliable.

A modification in the GEANT simulations to improve the transmission of the recoils was the tuning of an energy setting ± 3% relative to the standard. Our results suggested that the effect of this change in the transmission is <3% in all cases and the transmissions presented were achieved without it. However, it has been already successfully used in former DRAGON experiments, such as the ^{12}C$(\alpha,\gamma)^{16}$O study [28], and it could be used in ^{7}Be$(\alpha,\gamma)^{11}$C at any case.

Since no experimental angular distributions were known about those states, we ran simulations using different angular distributions for the γ-decays - dipole, quadrupole and uniform - to test their

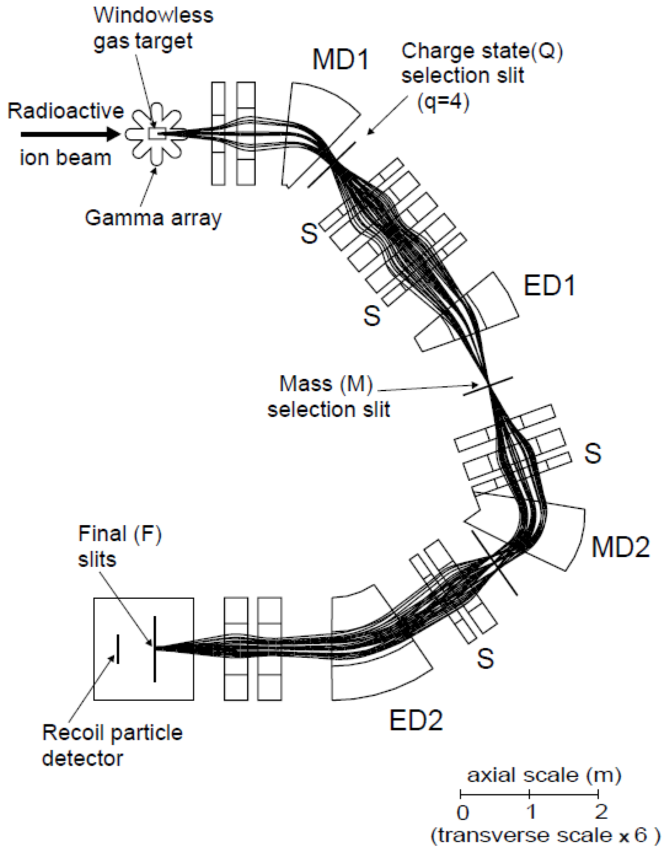


Figure 4: A schematic of the DRAGON facility. The four main components are shown: the windowless gas target, the BGO γ-ray detector array, the electromagnetic separator (EMS) and the recoil detection system. Figure reproduced from [23].

effect on the momentum cone and the transmission of the recoils. The results suggest that there is a relatively small sensitivity in the transmission, ± 2.8% for the 1110-keV, ± 1.5% for the 1155-keV resonance, and hence the BGO efficiency will be the dominant uncertainty in our measurements.

The beam current will be measured with Faraday cups located before the gas target and throughout the separator, and the separator will be tuned to transmit the most intense charge state of the beam[1]. The ionization chamber will provide ΔE-E discrimination and the BGO array along with Time-of-Flight separation will provide further identification of real events.

To calculate expected DRAGON yields, we assume resonance strengths in the range of 1-5 eV, based on constraining the combined contributions of these two resonances to the total rate. For instance, an upper limit of 1 eV in the resonance strength would limit this contribution to under 15% [30]. Considering a ^{7}Be beam intensity on the order of 10^{7} particles per second, 50% efficiency for the BGO array, 70% recoil detection efficiency, the CSF efficiency and the transmission of the recoils we expect $\sim$ 3-13 counts per shift for the E_r= 1110 keV resonance and $\sim$ 2-9 for the E_r= 1155 keV one. For the beamtime request estimates, we assume strengths of 1 eV and aim to detect 25 coincidence events for these two resonances. This will give us a 20% level of statistical uncertainty for each of them - and a lower level if the strengths turn out to be larger.

[1]For beam energies corresponding to the resonances of interest, the charge state distributions have been calculated according to Ref. [29].

Due to possible ^{7}Li contamination in the ISOL beam, some events from ^{7}Li$(\alpha,\gamma)^{11}$B reaction are expected. Separation of ^{11}C from ^{11}B recoils can be achieved by the ionization chamber that is currently used in DRAGON. Moreover, a new hybrid chamber in development in DRAGON could provide better separation. The amount of ^{7}Li in the ^{7}Be/^{7}Li ion beam will be measured with attenuated beam runs and the ionization chamber. In the energy region of interest, there are no known resonances of the $^7\mathrm{Li}+\alpha$ system within $\pm$ 20 keV of the relevant ^{11}C states (Figure 3). Nevertheless, ^{7}Li background runs will be performed to determine the contribution from this isobaric contaminant.

4 Beam Time Request

We request 32 shifts of ^{7}Be using a Tantalum target and the TRILIS ion source. This includes 26 shifts to measure the strengths for the three resonances of interest - E_r= 1110, 1155 and 1356 keV - and 6 shifts for off-resonance background measurements. In addition, we request 4 shifts using a stable ^{7}Li beam for isobaric contaminant measurements, 4 shifts using a ^{6}Li beam to measure ^{6}Li(α,γ) reaction as a calibration - E_r= 703 keV - and finally 2 shifts using a ^{12}C for charge state distributions. The total number of shifts requested are **42** (32 shifts of ^{7}Be (RIB) and 10 shifts of stable beam).

5 Readiness

The DRAGON facility is ready to perform this experiment. Yields with an average of about 4×10^7 particles per second have been already achieved at the ISAC yield station using the TRILIS Re Surface Ion Source from Tantalum #39 and #42 targets respectively [25], which should result in 10^7 particles per second on the windowless gas target. Concerning the stable beams, ^{6}Li, ^{7}Li and ^{12}C, they are delivered by OLIS from the Surface and the Multicharge Ion Source with intensities of 10^{11}, 10^{12} and 10^{12} particles per second respectively [31]. Furthermore, all equipment necessary to perform this experiment is available. Therefore, the experiment could run at the earliest opportunity, provided the committee grants the requested number of shifts.

6 Data Analysis

The data will be analyzed with personal computers at McMaster University and TRIUMF. Hence, no special data processing facilities will be required.

References

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31. OLIS Site.

Include publications in refereed journal over at least the previous 5 years:

1. D. Pérez-Loureiro, C. Wrede, M. B. Bennett, S. N. Liddick, A. Bowe, B. A. Brown, *A. A. Chen*, K. A. Chipps, N. Cooper, D. Irvine, E. McNeice, F. Montes, F. Naqvi, R. Ortez, S. D. Pain, J. Pereira, C. J. Prokop, J. Quaglia, S. J. Quinn, J. Sakstrup, M. Santia, S. B. Schwartz, S. Shanab, A. Simon, A. Spyrou, and E. Thiagalingam, *β-delayed γ decay of* ^{26}P *: Possible evidence of a proton halo* , Phys. Rev. C **93**, 064320 (2016).

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