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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

BEAM DEVELOPMENT FOR CHARACTERISING ^{19}Ne RESONANCES FOR EXPLOSIVE NUCLEOSYNTHESIS

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Abstract: A request for six shifts to measure yields and contaminants for beams of ^{18}Ne. The ^{19}Ne nucleus is a key isotope in nuclear astrophysics due to its role in both the $^{15}\mathrm{O}(\alpha,\gamma)^{19}\mathrm{Ne}$ and $^{18}\mathrm{F}(p,\alpha)^{15}\mathrm{O}$ reactions in Type I x-ray bursts and novae, respectively; energy levels in ^{19}Ne around the α and proton thresholds (3529 keV and 6410 keV) form resonances in the cross sections for both of these reactions. Beam development for ^{18}Ne will allow studies of the structure of ^{19}Ne in these key energy regions via the $d(^{18}\mathrm{Ne},p)^{19}\mathrm{Ne}$ reaction. From previous studies, discrepancies in the energies, spin-parities, and branching ratios for levels in ^{19}Ne have been found to contribute to the astrophysical reaction rate uncertainties. A ^{18}Ne beam corresponding to yields approaching $10^6/\mu$C in conjunction the ISOLDE Solenoidal Spectrometer will allow the exploration of states across these energy regions in around 20 shifts. The proposed set-up uniquely offers the opportunity to cleanly measure the high-resolution excitation spectra, infer spin-parities of key states through angular distribution analyses, while simultaneously being sensitive to their branching ratios.

Summary of requested shifts: 6 shifts

1 Physics cases

The nuclear structure of ^{19}Ne above the α and proton thresholds is important for accurate estimations of the nucleosynthesis occurring in Type I x-ray bursts and novae. The energy levels near the α threshold (3529 keV) correspond to resonances in the $^{15}\mathrm{O}(\alpha,\gamma)^{19}\mathrm{Ne}$ cross section, which is important for break-out from the hot carbon-nitrogen-oxygen (CNO) cycles [6] into the rapid proton capture (rp) process [1, 2], as depicted in figure 1. The rp-process converts the light element fuel into heavy elements in just a few seconds, causing a sudden release of energy and driving x-ray bursts [3]. These bursts occur in the atmosphere of an accreting neutron star in a close binary system [4, 5].

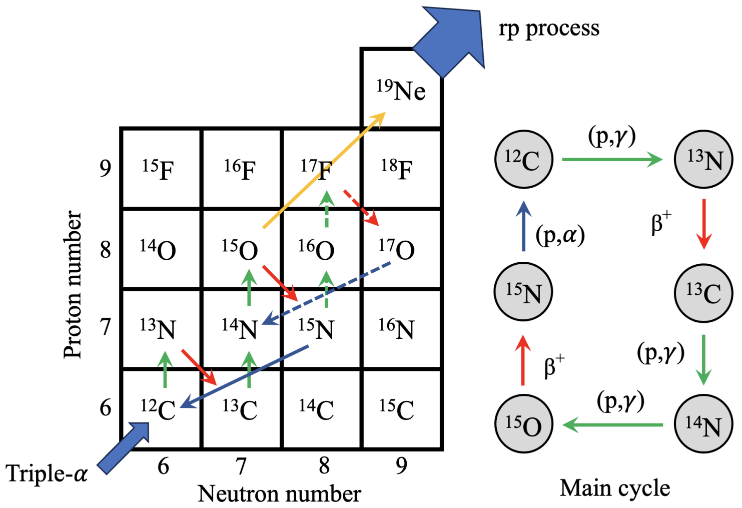

Figure 1: The hot CNO cycle (temperatures above 100 MK) converting four hydrogen nuclei into helium, and the breakout reaction $^{15}\mathrm{O}(\alpha,\gamma)^{19}\mathrm{Ne}$, which leads to the rp-process.

Since the direct capture contribution is negligible over the astrophysical temperature range [7], resonances near the α-decay threshold in ^{19}Ne, especially the narrow $3/2^+$ state at 4.03 MeV, will dominate the reaction rate [8]. This state has a well-known lifetime, so only a finite value for the small α-particle branching ratio is needed to determine the reaction rate. There have been attempts to measure Γ_α/Γ using direct reactions to populate the 4.03 MeV state, but these have only yielded a firm upper limit of $(2.9 \pm 2.1) \times 10^{-4}$ [9].

Other near-threshold states at 4.14 and 4.2 MeV still have unknown spin-parities. It is thought that they are $7/2^-$ and $9/2^-$ but due to their close proximity, the order is uncertain [10]. The current alpha-branching ratio for these two levels combined is $(1.2 \pm 0.5) \times 10^{-3}$ [10]. It was noted by Ref. [10] that the upper limit they obtained for the α branching ratio was unexpectedly large and might indicate a possible α-cluster configuration. The relatively large width gives these states a more significant role in hot CNO break out despite their larger angular momenta – dominating in some temperature regimes. Despite experimental efforts, the α-cluster nature of these two levels remains tentative [15]. Spin-parity assignments are required to calculate reduced α widths, for comparisons with other states belonging to a predicted $^{15}\mathrm{O} + \alpha$ rotational band [16].

Higher energy levels in ^{19}Ne above the proton threshold (6410 keV) are also accessible using this same experimental technique and settings, without the need for magnetic field or beam energy changes. These states determine the rate that ^{18}F is destroyed by proton-induced reactions during nova explosion nucleosynthesis [11]. The 511-keV γ-ray line and lower-energy continuum generated during the β^+ decay of ^{18}F is a candidate for observing novae with space-based γ-ray observatories [12]. Accurately calculating the abundance of ^{18}F nuclei remaining after the explosion is a key input for determining the distances at which γ rays from novae can be detected and the necessary telescope sensitivities.

Energy levels with spin-parities of $1/2^+$ or $3/2^+$ dominate the reaction rate because they correspond to s-wave resonances. Therefore, accurately measuring the spin-parities, energies and proton widths of near-threshold levels is key. The dominant $3/2^+$ state is at 7.757 MeV, which is broad, meaning it will influence the proton capture over a large temperature range [14]. However, other nearby resonances remain less well-characterised.

In a future experiment, we wish to populate the 4.03, 4.14 and 4.2 MeV states in ^{19}Ne via the $d(^{18}\text{Ne},p)^{19}$Ne reaction at 10 MeV/u, detecting protons in the backward angles in the ISOLDE Solenoidal Spectromenter (ISS). These will form angular distributions to assist with spin-parity assignments of the 4.14 and 4.2 MeV states. A downstream $\Delta E - E$ detector will permit branching ratio measurements for all three resonances. In addition, higher excited states above the proton threshold may also be measured using ISS with the same experimental settings. The proposed experimental set-up will be sensitive to their proton partial widths by detecting ^{18}F recoils in the $\Delta E - E$ telescope.

For such measurements, we would require beams at energies at 10 MeV/u at intensities approaching 10^5 pps to perform an experiment in a reasonable time, corresponding to yields around $10^6/\mu$C.

The goal of this Letter of Intent

This letter of intent requests time for ^{18}Ne beam development using CaO, MgO and SiC targets. Two shifts per target will allow for target and source optimisation. We first describe the experimental set-up of a future proposal with ISS and then describe the aims of the currently requested beam development time.

2 Experiment Set-up

We propose to use ^{18}Ne from HIE-ISOLDE together with the ISOLDE Solenoidal Spectrometer (ISS) to measure the $d(^{18}\text{Ne},p)^{19}$Ne reaction at 10 MeV/u. We intend to use a very similar setup that was already successfully used by the ISS collaboration, to measure the $d(^{7}\text{Be},p)^{8}$Be reaction [17], which included mounting the downstream recoil telescope at much closer distances to the target than in earlier work [18]. A three-dimensional rendering of the proposed set-up is shown in figure 2.

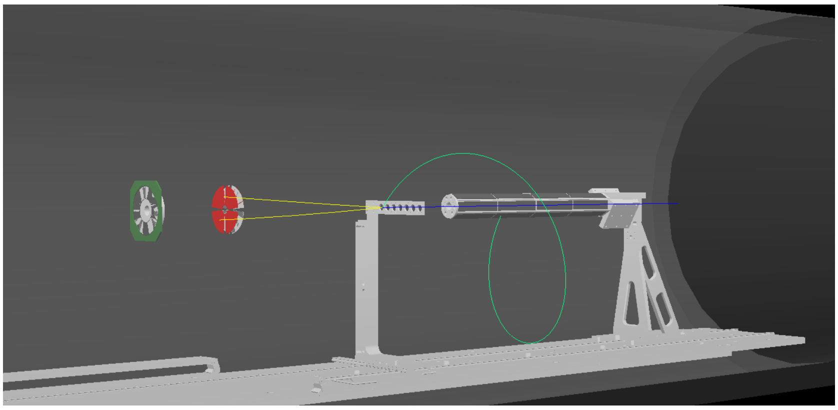

Figure 2: Three-dimensional rendering of the proposed experimental set-up and a simulated event where ^{19}Ne decays into ^{15}O + α. Generated using NPtool.

A valid proton event will require a signal in the ISS hexagonal proton detector placed in the backward angles (at a target-to-array distance of 30cm) in coincidence with a heavy ion in the recoil detector placed in the forward angles. The recoil detector comprises a 65 μm-thick and a 500 μm-thick QQQ1 double-sided silicon detector (Micron Semiconductor Ltd) in a $\Delta E - E$ telescope configuration. The QQQ1 detector is arranged in a four quadrant circular geometry, with an outer diameter of 10 cm and a 1.8 cm hole in the center, for passage of unscattered beam. It will be placed 40 cm downstream from the target and subtend an angular range of $2.5 - 14°$ in the laboratory frame. The area of the hole in the center amounts to only 3.2% of the total area, leading to a high efficiency for detecting charged particles that are emitted in the forward angles.

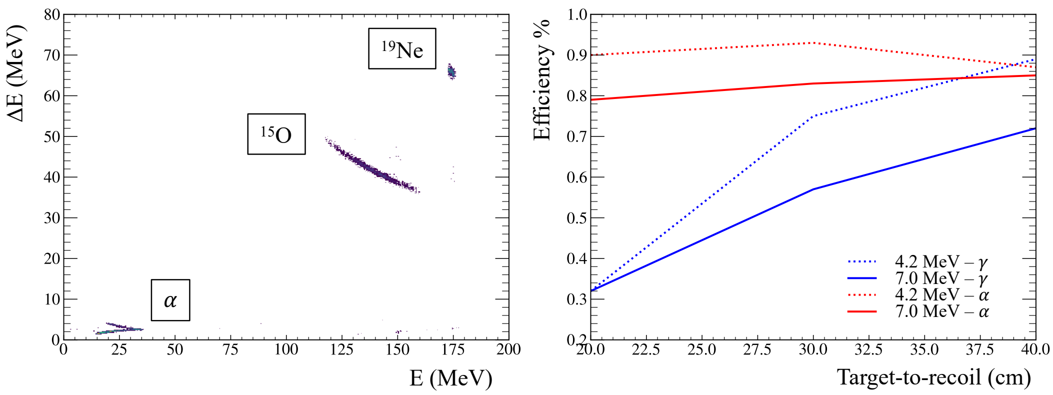

Figure 3: Right: The $\Delta E - E$ spectrum generated for different decay modes of the 4.2 MeV state in ^{19}Ne. Left: Plot of recoil coincidence efficiency for different decay channels and state energies. Generated using NPtool.

The recoil $\Delta E - E$ detector will be used to detect either the ^{19}Ne, which will often γ decay, or its charged decay products (α, p, ^{15}O, ^{19}F). The left panel of figure 3 shows simulations for the γ and α decay of the 4.2 MeV state in ^{19}Ne, demonstrating the ability to cleanly separate the two channels using the recoil detector. The proposed target-to-recoil distance was optimised to 40 cm to maintain a high efficiency for detecting ^{15}O from the α decay of the 4.2 MeV state in ^{19}Ne, while increasing the efficiency for ^{19}Ne collection. These calculations are shown in the right panel of figure 3. For protons hitting the array after populating the 4.2 MeV state, 90% of these events will result in a coincidence in the recoil telescope for both the ^{15}O + α and γ-decay channel.

The beam intensity will be monitored using a separate luminosity monitor detector, which measures elastically scattered deuterons that are bent by the magnetic field around the recoil detector. Absolute beam intensity may also be verified by scaling to the cross sections for populating well characterised states in ^{19}Ne.

The ISS magnet will be operated at 2 Tesla and the resulting proton kinematics in the ISS are shown in the left panel of figure 4. The strength of the magnetic field was chosen to ensure sensitivity to measurements of the angular distributions over the range of $10 - 45°$ in the centre of mass, where the cross sections are meant to be largest for populating key states of interest, and show the enough variation for making spin-parity assignments. A simulated excitation energy spectrum showing the separation of the 4.03, 4.14 and 4.2 MeV states at the expected statistics is shown in the right panel of figure 5. Although the 4.03 MeV state is nicely resolved, the 46 keV resolution is not sufficient to separate the 4.14 and 4.2 MeV states by eye. However, with the expected statistics, and a well-characterised resolution, a restricted two-peak fit to the spectrum can separate each component for an angular analysis. The α decay branching ratio will be evaluated for the two resonances combined due to this limitation.

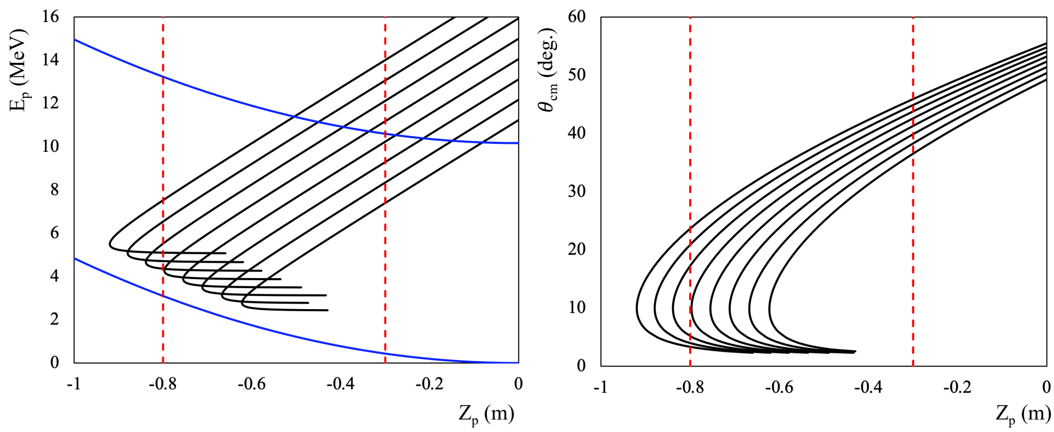

Figure 4: Left: The kinematics of proton detection in the ISS leading to measured centre of mass angles of $10 - 45°$.

Preliminary calculations of differential cross sections were obtained using FRESCO, where the narrow unbound states were approximated by a continuum bin. These calculations, with an example shown in the left panel of figure 5, allow us to determine an approximate reaction rate for populating the states of interest. They also highlight the necessary sensitivity for assigning spin-parities of key states. For example, figure 5 demonstrates the ability to distinguish whether the 4.2 MeV state in ^{19}Ne is $7/2^-$ or $9/2^-$. The two transfers exhibit behaviours in the measured angular range.

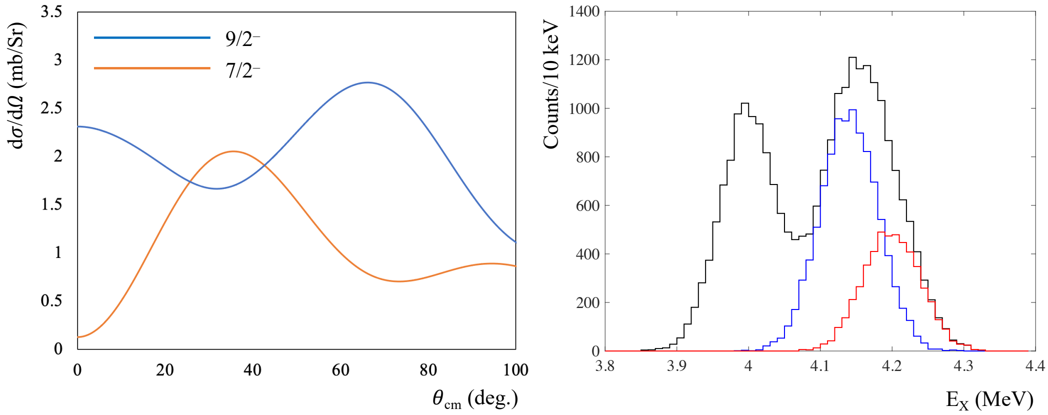

Figure 5: Left: The DWBA calculations performed using FRESCO, showing angular distributions for populating a 4.2 MeV state. Right: Simulation showing the resolving power between key states. Ten thousand and five thousand counts per resonance were simulated.

3 Beam development

For successful realisation of the physics goals within a reasonable timeframe (20 shifts), a 10 MeV/u ^{18}Ne beam extracted from HIE-ISOLDE will be required at a beam intensity approaching 10^5 pps into ISS. This will theoretically permit measurements of the key α-decaying states and extracting α branching ratios with 30% statistical uncertainties.

This corresponds to target yields above $10^6/\mu$C assuming a 5% transmission efficiency. According to the ISOLDE yield database [19] high yields were reported from CaO and MgO targets, but these results have not been reproduced in over 20 years.

Recent measurements using nanometric CaO targets indicated yields two orders of magnitude lower compared to the yield database values. Yields from such target-ion source systems are known to vary considerably, potentially due to varying ion source efficiencies [20]. In addition, neon was not the primary interest of the measurement campaign at that time. To address this, we propose conducting dedicated yield measurements under this LOI.

Magnesium oxide (MgO) has not been utilised as target material in recent years, thus requiring both development and yield measurements. Another promising candidate is SiC, which offers higher in-target production rates compared to CaO [19]. Silicon carbide was available in submicron microsutructures in the past, fostering diffusion characteristics, which makes this material a strong alternative. Since it was likewise not used in recent years, it requires development and yield measurements.

In total, we therefore request a total of **6 shifts** (2 per material) for yield measurements and ion source optimisation. We anticipate that a full proposal will be submitted following a successful conclusion to these measurements.

References

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4 Details for the Technical Advisory Committee

4.1 General information

Describe the setup which will be used for the measurement. If necessary, copy the list for each setup used.

☒ Permanent ISOLDE setup: *Name (e.g. CRIS, IDS, Miniball, etc.)*

- ☒ To be used without any modification
- ☐ To be modified: *Short description of required modifications.*

☐ Travelling setup (*Contact the ISOLDE physics coordinator with details.*)

- ☐ Existing setup, used previously at ISOLDE: *Specify name and IS-number(s)*
- ☐ Existing setup, not yet used at ISOLDE: *Short description*
- ☐ New setup: *Short description*

4.2 Beam production

For any inquiries related to this matter, reach out to the target team and/or RILIS (please do not wait until the last minute!). For Letters of Intent focusing on element (or isotope) specific beam development, this section can be filled in more loosely.

- Requested beams:

Isotope	Production yield in focal point of the separator (/μC)	Minimum required rate at experiment (pps)	$t_{1/2}$
Isotope 1 Isotope 2 Isotope 3	10^6	10^5	1.6656 s

- Full reference of yield information (*e.g. yield database, elog entry, previous experiment number, extrapolation and/or justified scaling factors, target number*)
- Target - ion source combination: CaO, MgO, SiC
- RILIS? (*Yes*)
  - ☐ Special requirements: (*isomer selectivity, LIST, PI-LIST, laser scanning, laser shutter access, etc.*)
- Additional features?
  - ☐ Neutron converter: (*for isotopes 1, 2 but not for isotope 3.*)
  - ☐ Other: (*quartz transfer line, gas leak for molecular beams, prototype target, etc.*)
- Expected contaminants: *Isotopes and yields*

- Acceptable level of contaminants: (*Not sensitive to stable contaminants, limited by ISCOOL overfilling, etc.*)
- Can the experiment accept molecular beams?
- Are there any potential synergies (same element/isotope) with other proposals and LOIs that you are aware of?

4.3 HIE-ISOLDE

For any inquiries related to this matter, reach out to the ISOLDE machine supervisors (please do not wait until the last minute!).

- HIE ISOLDE Energy: *(MeV/u); (exact energy or acceptable energy range)*
  - ☒ Precise energy determination required
  - ☐ Requires stable beam from REX-EBIS for calibration/setup? *Isotope?*
- REX-EBIS timing
  - ☒ Slow extraction
  - ☐ Other timing requests
- Which beam diagnostics are available in the setup?
- What is the vacuum level achievable in your setup?

4.4 Shift breakdown

The beam request only includes the shifts requiring radioactive beam, but, for practical purposes, an overview of all the shifts is requested here. Don't forget to include:

- Isotopes/isomers for which the yield need to be determined
- Shifts requiring stable beam (indicate which isotopes, if important) for setup, calibration, etc. Also include if stable beam from the REX-EBIS is required.

An example can be found below, please adapt to your needs. Copy the table if the beam time request is split over several runs.

Summary of requested shifts:

With protons	Requested shifts
Yield optimisation of isotope 1 using CaO target	2
Yield optimisation of isotope 1 using MgO target	2
Yield optimisation of isotope 1 using SiC target	2
Without protons	Requested shifts
Stable beam from REX-EBIS (after run)	
Background measurement	

4.5 Health, Safety and Environmental aspects

4.5.1 Radiation Protection

- If radioactive sources are required:
  - Purpose?
  - Isotopic composition?
  - Activity?
  - Sealed/unsealed?
- For collections:
  - Number of samples?
  - Activity/atoms implanted per sample?
  - Post-collection activities? (*handling, measurements, shipping, etc.*)

4.5.2 Only for traveling setups

- Design and manufacturing
  - ☒ Consists of standard equipment supplied by a manufacturer
  - ☐ CERN/collaboration responsible for the design and/or manufacturing
- Describe the hazards generated by the experiment:

Domain	Hazards/Hazardous Activities		Description
Mechanical Safety	Pressure	☐	[pressure] [bar], [volume][l]
	Vacuum	☐	
	Machine tools	☐	
	Mechanical energy (moving parts)	☐	
	Hot/Cold surfaces	☐	
Cryogenic Safety	Cryogenic fluid	☐	[fluid] [m3]
Electrical Safety	Electrical equipment and installations	☐	[voltage] [V], [current] [A]
	High Voltage equipment	☐	[voltage] [V]
Chemical Safety	CMR (carcinogens, mutagens and toxic to reproduction)	☐	[fluid], [quantity]
	Toxic/Irritant	☐	[fluid], [quantity]

	Corrosive	☐	[fluid], [quantity]
	Oxidizing	☐	[fluid], [quantity]
	Flammable/Potentially explosive atmospheres	☐	[fluid], [quantity]
	Dangerous for the environment	☐	[fluid], [quantity]
Non-ionizing radiation Safety	Laser	☐	[laser], [class]
	UV light	☐	
	Magnetic field	☐	[magnetic field] [T]
Workplace	Excessive noise	☐	
	Working outside normal working hours	☐	
	Working at height (climbing platforms, etc.)	☐	
	Outdoor activities	☐	
Fire Safety	Ignition sources	☐	
	Combustible Materials	☐	
	Hot Work (e.g. welding, grinding)	☐	
Other hazards			