EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Using in-trap decay to provide inaccessible and low-yield isotopes to the ISOLDE facility

January 10, 2024

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CERN-INTC-2024-015 / INTC-I-270
10/01/2024

Abstract: We intend to explore the use of in-trap decay as a beam production mechanism at ISOLDE. Specifically, we intend to use the ISCOOL radiofrequency quadrupolar cooler-buncher to trap short-lived ions for several half-lives and allow them to decay within the trap, contain their daughter nuclei within the trap potential, and deliver them as a radioactive beam for study. In-trap decay as a beam production approach could provide access to isotopes that are currently inaccessible due to the refractory or reactive nature of their atoms. As a commissioning study, we request 6 shifts to test and optimize the properties of ISCOOL for the in-trap decay of ^{34}Mg into

^{34g,m}Al, and their subsequent decay into ^{34}Si. The ISOLDE Decay Station and ISOLTRAP will be used for detection and diagnostics, also allowing a direct measure of the approach's efficiency of delivery to ISOLDE experiments.

Requested shifts: 6 shifts

1 ISOL beams and beyond

The isotope separation on-line (ISOL) method [1, 2] of producing short-lived radioactive beams has been a cornerstone of research in nuclear structure for more than half a century. The ISOLDE facility at CERN [3], the first facility to utilize the ISOL method, remains at the forefront of precision studies in nuclear, fundamental, solid-state, and biological physics and astrophysics, thanks to the intense and isotopically pure beams it can continuously deliver for the majority of the calendar year.

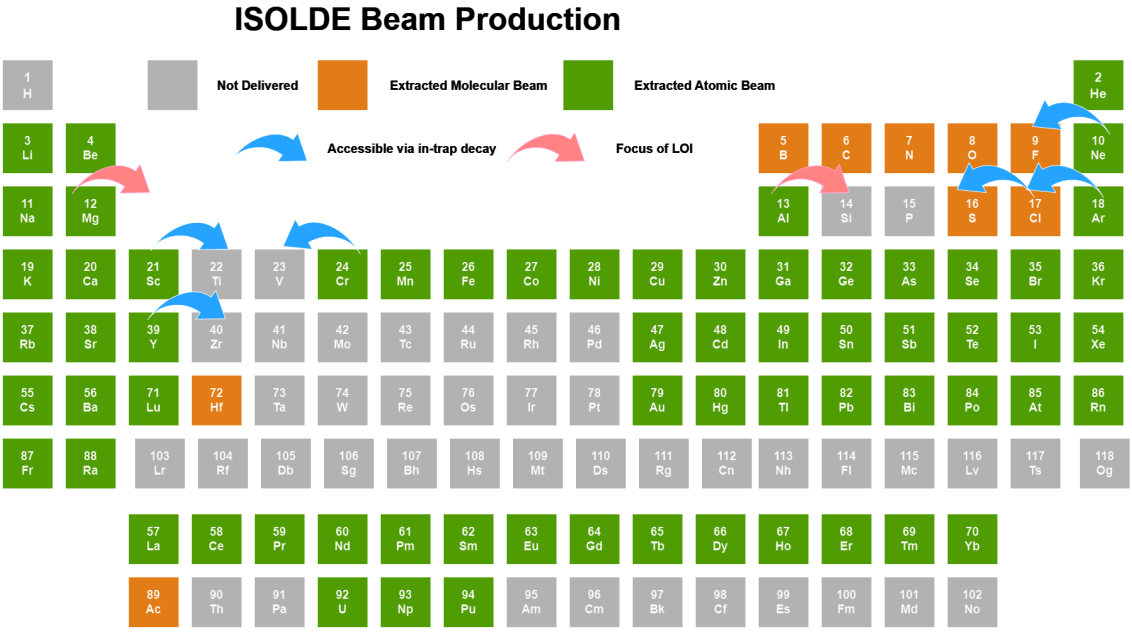

Figure 1: Periodic table illustrating the production of elements at ISOLDE. The colour of the boxes indicates whether the isotopes are extracted in atomic or molecular form [4, 5, 6]. The grey boxes represent the isotopes which cannot be extracted. The blue arrows display possible isotopes that can be accessed with the in-trap decay and the pink arrows represent the isotopes which will be the focus of this LOI.

With the ISOL method, radionuclides are produced by bombarding energetic beams of light particles (commonly protons) onto a target of heavy, stable nuclei. The bombardment induces a number of different nuclear reactions, depending on the combination of primary beam, target material, and projectile energy, producing nuclei at a very wide range of proton and neutron numbers. At ISOLDE, more than 1,000 different isotopes and isomers of 76 elements have been produced and delivered for study [7]. Thanks to continuous developments in ion source design and the use of magnetic separators with high resolving power, the nuclides are delivered for study as intense and isotopically pure ion beams. Notably, ISOLDE can deliver a large range of isotopes of a given element within the same experimental run, enabling extensive studies of isotopic chains within a

short period of time.

While practically all nuclides lighter than the target material are produced within the ISOL target, including few elements above the target mass [8], nuclei whose atoms are reactive or refractory cannot be efficiently extracted from the source as atomic ion beams and delivered for study [9]. As a result, the isotopes of these elements exhibit glaring gaps in the part of the nuclear chart that has been studied with laser spectroscopy [10].

A lot of target and ion-source development efforts have been dedicated to enabling the delivery of nuclides with reactive or refractory atoms following the thick-target ISOL production at facilities such as ISOLDE and TRIUMF. The central principles of the majority of these efforts at ISOLDE are target material developments [11] and the controlled formation of molecular beams with more favorable chemical properties (e.g. vapor pressure and enthalpy of adsorption on wall surface) than the radioactive atoms of interest [9]. Molecular formation involves introducing a chemical agent into the container of a standard target and ion source unit (see for instance Refs. [9, 12, 13, 4, 5]), or the design of a novel ion source altogether [14, 15, 16]. These efforts have successfully delivered molecular beams of short-lived nuclides for many otherwise inaccessible elements at ISOLDE, and a large number of elements with producible atomic ion beams, allowing for a direct comparison of extraction efficiency [6].

With this Letter of Intent, we request 6 shifts to explore an additional pathway to delivering otherwise inaccessible radionuclides far from stability, based on in-trap decay of their parent nuclides that can be produced efficiently at ISOLDE. We intend to utilize the ISCOOL [17] radiofrequency cooler-buncher to trap the well-produced parent nuclei for several half-lives and trace the parent-daughter ratio in the extracted beam using the ISOLDE Fast Tape Station (FTS) [18], the ISOLDE Decay Station (IDS) and the ISOLTRAP multi-reflection mass spectrometer (MR-ToF MS). This approach has the benefit of delivering the nuclides of interest in atomic form, as opposed to molecular beam extraction, which is necessary for certain experimental techniques, such as laser spectroscopy, implantation, and antimatter annihilation experiments. Moreover, isomeric states that are not produced with the ISOL method but are efficiently populated via nuclear decay can be delivered with this approach.

2 In-trap decay for isotopes far from stability

In-trap β-decay studies have significantly gained momentum in recent years, being an eminent area of research investigating the angular correlations of β-decay and for tests of the weak interaction in the Standard Model [19, 20, 21, 22]. Two pioneering groups currently operating in this field are at GANIL [23] and Argonne [22], which have successfully illustrated the effectiveness of this technique. Previous experimental campaigns using a linear Paul trap to perform in-trap decay have been conducted on He [20], Li and B [19, 22], and Sb [21]. The focus of these campaigns was placed

on the high-precision detection of the β particles ejected following β decay using a series of detectors surrounding the linear Paul trap. Most recently, this technique was demonstrated using $^{8}Li^{+}$ and $^{8}B^{+}$. These ions were independently trapped in a Paul trap and allowed to decay, with the subsequent β-particles being detected using an array of silicon detectors surrounding the trap, and the daughter nuclei being confined within the trapped ion cloud. Despite the large Q values of ^{8}Li ($Q_{\beta^-} = 16.00413(6)$ MeV) and ^{8}B ($Q_{\beta^+} = 16.9579(10)$ MeV), a trapping efficiency of 25% of the daughter nuclei with a 3.375 mm^3 ion-cloud confinement region was achieved [22].

The principle of operation for this technique relies on injecting a short-lived nucleus into the Paul trap and trapping it for a sufficient time to allow for the majority of the ion ensemble to decay. By optimising the properties of the Paul trap, such as the quadrupolar RF (V_{pp} and ω), potential well depth, and buffer gas pressure, the ion-cloud confinement can be optimized to trap the recoiling daughter and granddaughter nuclides. These nuclides are then ejected from the trap and sent to a subsequent experimental setup or detector.

One of the crucial considerations for this method is accounting for the magnitude of the Q value, which is directly related to the recoil energy of the daughter nucleus. The larger this value is, the greater the recoiling energy of the daughter nuclei. This has to be accounted for by the trapping properties of the Paul trap to ensure that the trapped ions remain confined within the ion cloud following β decay. Given the opportunity to optimise the properties of the Paul trap, the decay products can be successfully confined, as demonstrated by Varrianno *et al.,* despite the large Q values of ^{8}Li and ^{8}B [22]. For the proposed approach of in-trap decay as a production mechanism, other properties of the parent nuclides must also be considered, such as the ratios of half-lives between the parent and daughter nuclei, the decay branching ratios, the release time of the parent nuclides from the ISOLDE target production, and the space-charge limit of the trap. All of these properties can influence both the efficiency of the in-trap decay production method and the extraction of the daughter nuclei from the Paul trap. Many of these considerations can be rectified by time-synchronising the proton impact trigger with the injection and extraction electrodes and calculating a specific trapping time for the injected species.

The in-trap decay approach can open new production avenues at ISOLDE for nuclides and their isomers that are currently difficult to access due to their reactive or refractory atomic properties, as shown in Fig. 1. In particular, the lighter elements, such as Si, P, S, and Cl, are notably difficult to extract in atomic form, but are regions rich with interesting nuclear structure phenomena, such as the rapid onset of deformation in the $N = 20$ and 28 islands of inversion [24], the bubble nucleus of ^{34}Si [25], and the possible appearance of new magic numbers at $N = 14, 16, 32$ [26, 27, 28]. Other areas of interest may be of low-yield cases, such as neutron-rich Ca, which could be produced through the in-trap decay of the more easily extracted K [29], or the production of isomers that cannot be formed through the typical ISOL production method, such as ^{34m}Al [30].

3 Beam request

As a proof-of-principle case, the in-trap decay of ^{34}Mg can be tested for the production of the ^{34m}Al isomeric state ($I^\pi = 1^+$), which has not been observed in direct production from ISOLDE. These nuclei have been extensively studied at IDS and a large number of γ lines are known, including the nuclides' half-lives and branching ratios [30]. Moreover, the subsequent decay of ^{34g,m}Al into ^{34}Si will be investigated. Silicon isotopes are of great importance for nuclear and solid-state physics [31], but no radiogenic Si beams have been successfully produced at ISOLDE to date.

Table 1: Summary of the relevant properties of the nuclides involved in the beam request. The percentage values in brackets represent the β decay branching ratios from the decay of ^{34}Mg. Half-lives and β feeding ratios taken from the IDS study in Ref. [30].

Isotope	I^π	$T_{1/2}$ (ms)	Trap time ($5T_{1/2}$) (ms)	Q value (keV)	ISOLDE yield (s^{-1} μC^{-1})
Parent					
^{34}Mg	0^+	44.9(4)	224.5(20)	11321 (7)	140
Daughters					
^{34m}Al (>99%)	1^+	22.1(2)	110.5(10)		/
^{34g}Al (0.3(1)%)	4^-	53.73(13)	268.65(65)	16994.1 (23)	86
Granddaughter					
^{34}Si	0^+	2,770(200)			/

Therefore, we request 6 shifts with protons for the delivery of ^{34}Mg with RILIS, using a standard UC_x unit. We intend to identify the in-trap decay products using both γ-ray detection at the FTS and IDS and the MR-ToF MS at ISOLTRAP. Spectroscopy of the γ lines is the critical diagnostic that will provide the background-free detection of the desired decay products and their ratio with respect to the parent, while the MR-ToF MS will inform us of the parasitic molecular formation due to the extended interaction of the trapped ions with impurities in the helium buffer gas [32] in ISCOOL.

An overview of the requested shift allocation is presented in Table 2 and the relevant properties of the nuclides involved in our proposed investigation are listed in Table 1. The first two shifts will be dedicated to ion delivery to both ISOLTRAP and IDS with a continuous beam and ISCOOL in pass-through mode. Excellent transmission and efficient switching between set-ups is crucial to the success of this LOI. This stage will be completed using a stable or a high-yield isotope. Once a sufficient transmission is obtained, the ISCOOL device will be set to trapping operation and the mass will be adjusted to ^{34}Mg. Using a trapping time of 20 ms, a reference ion count rate ratio between ^{34}Mg and ^{34m}Al will obtained using the IDS set up, and any molecular formation will be identified using the ISOLTRAP MR-ToF MS.

Following this, the trapping duration of the ISCOOL device will be increased to 224.5 ms, equating to $5T_{1/2}$, as shown in Table 1. The RF properties, the well depth and the gas pressure of the ISCOOL device will be optimised to improve the production and count rate of ^{34m}Al beam. The ion beam injection will be time-synchronised with the proton impact and the release time of the magnesium ion beam from the UC_x, to minimise any contamination entering ISCOOL at differing release times. As the ions will be confined within the ISCOOL device for prolonged time periods, additional MR-ToF MS scans will be recorded to observe any molecular formation caused by the additional trapping time. As this is the priority of the LOI, this will take 3 shifts to complete.

Previously, the formation of ^{34m}Al via in-trap decay was performed at ISOLTRAP using a gas-filled Penning trap [33] with decay-capture efficiencies of up to 25%. Furthermore, indications of capturing the beta-decay daughter of ^{27}Na in the ISOLTRAP Paul trap had been found during half-life measurements of ^{27}Na in Ref. [34], encouraging the potential of using linear Paul traps at ISOLDE to provide certain isotopes of refractory elements. Our proposed tests allow for the opportunity to reproduce and improve the results previously observed in Refs. [33, 34], which serve as a benchmark for this LOI.

The final objective of the LOI will be to adjust the mass of the ion beam to ^{34g}Al and prolong the trapping time to 268.65 ms in order to produce ^{34}Si. Due to the higher Q value of 16994.1 (23) keV for the β-decay mechanism and thus the higher recoiling energy of the daughter nuclei, further optimisation of the RFQ will likely be required to confine the ions within the RFQ. One shift has been dedicated to the production of ^{34}Si.

Table 2: Shift allocation for the proposed LOI to perform in-trap decay of ^{34}Mg and ^{34m}Al.

Objective	Shift(s)
Ion Transmission and referencing	**2**
In-trap decay of ^{34}Mg and ISCOOL Optimisation	**3**
In-trap decay of ^{34m}Al	**1**

Summary of requested shifts: 6 shifts with protons for the delivery of ^{34}Mg with RILIS from a standard UC_x target.

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DESCRIPTION OF THE PROPOSED EXPERIMENT

Please describe here below the main parts of your experimental set-up:

Part of the experiment	Design and manufacturing
If relevant, write here the name of the fixed installation you will be using [Name fixed/present ISOLDE installation: e.g. COLLAPS, CRIS, ISS, Miniball etc]	☒ To be used without any modification ☐ To be modified
If relevant, describe here the name of the flexible/transported equipment you will bring to CERN from your Institute [Part 1 of experiment/ equipment]	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[Part 2 of experiment/ equipment]	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[insert lines if needed]	

HAZARDS GENERATED BY THE EXPERIMENT

Additional hazard from flexible or transported equipment to the CERN site:

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			