EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

α-scattering on heavy unstable proton-rich nuclei in inverse kinematics at energies around the Coulomb barrier for the astrophysical p-process

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Abstract: Recent developments in target production allow for the measurement of α-particle induced reactions in inverse kinematics, opening a new window in the study

of α-nuclear interactions with exotic beams at low energies. Due to the lack of experimental data in the region around the heavy p-nuclei, uncertainties in the astrophysical modelling of the p-process is still dominated by the α-nuclear potential. The use of long-lived radioactive beams in this mass region at energies around the Coulomb barrier (available now at HIE-ISOLDE) surrounded by position-sensitive charged particle detectors provides an unique opportunity to validate models and to reduce the uncertainties in the nuclear potential, and consequently of the astrophysical modelling.

1 Introduction

The bulk of the heavy nuclei are produced via neutron capture reactions in the *s*- and the *r*-process [1, 2]. Additional neutron capture process like the *i*-process [3] also significantly contribute to the synthesis of nuclei heavier than iron. However, there is a small amount of nuclei ranging from ^{74}Se till ^{196}Hg which cannot be produced by these processes due to the presence of stable isomer nuclei with lower atomic number, hindering their production through neutron induced reactions. The production of the so-called *p*-nuclei is mostly thought to happen via the *p*-process [4] (sometimes described as γ-process [5]) in the O/Ne layer of Supernovae Type II explosions, reaching temperatures in the order of T_9 = 1.5 - 3.5.

Over the past years, several sensitivity studies [5, 6, 7, 8] have been performed in order to identify the uncertainties caused by the nuclear input in reaction networks aiming at describing the production of the *p*-nuclei. All studies indicated a strong dependence of the final abundance distribution of the heavy *p*-isotopes on the α-nuclear potential, highlighting the strong need of characterising α-particle induced reactions, among others, on the long-lived nuclei ^{148}Gd, ^{150}Gd, ^{152}Gd, ^{154}Dy, and ^{174}Hf. Despite the astrophysical *p*-process, α-particle induced reaction cross sections play an essential role under certain *r*-process conditions [9, 10, 11], and well as in the α *p*-process [12].

Over the past two decades, there has been a strong effort in characterising the potential describing the interaction of α-particles with heavier nuclei at energies as close as possible to those relevant for nuclear astrophysics, both from the experimental [13, 14, 15] and from the theoretical [16, 17] sides. However, due to the very low relative abundance of the *p*-nuclei in the mass region at which the α-nuclear potential provides the highest uncertainty, it is extremely challenging the production of stable targets sufficiently enriched to perform these studies in direct kinematics. As such, the heaviest *p*-nucleus studied in α-scattering experiments is ^{144}Sm [18].

Recent advances in the technique of magnetron sputtering allowed the production of self-supporting films of Si containing large quantities of ^{4}He, reaching values around 10^{18} atoms/cm^2 [19, 20]. This can be used as targets in nuclear reaction experiments to measure elastic scattering and determine nuclear optical potentials, providing a clear opportunity to study radioactive nuclei in inverse kinematics using state of the art charged particle detection systems covering large solid angle while allowing for a precise determination of the entrance angle of the particles emerging from the reaction process.

A proposal to implement these enormous advances in target development to characterise for the first time the α-nuclear potential in unstable proton rich nuclei at the HIE-ISOLDE facility is in progress. However, the shutdown period at CERN over 2019 and 2020 offers an unique window of opportunity to study for the first time the elastic α scattering of long-lived radioactive isotopes like ^{148}Gd, ^{150}Gd, ^{152}Gd, ^{154}Dy, or ^{174}Hf, all of them relevant for nuclear astrophysics purposes, at energies close to the Coulomb barrier, around 5 MeV/u, in inverse kinematics at the HIE-ISOLDE facility.

Complementarily, the study of even-Z odd-N isotopes in the same region, with relatively shorter half life, like ^{151}Gd or ^{159}Dy, would also significantly contribute to improve the description of the interaction of α-particles with heavy nuclei. Even reactions on stable p-isotopes like ^{156}Dy or ^{164}Er would result in a tremendous advance for the field. These measurements will allow for a precise knowledge of the α-nuclear potentials in this mass region, resulting in a clear reduction of uncertainties in the astrophysical models.

This letter expresses the strong interest in the use of long-lived radioactive nuclei, with special focus in the nuclei previously listed, to study and experimentally determine the α-nuclear potential of heavy unstable proton-rich nuclei at energies close to the Coulomb barrier using the HIE-ISOLDE beam line. A proposal to perform these measurements will be submitted in the case these beams are available.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT
The experimental setup comprises: (*name the fixed-ISOLDE installations, as well as flexible elements of the experiment*)

Part of the	Availability	Design and manufacturing
(if relevant, name fixed ISOLDE installation: MINIBALL + only CD, MINIBALL + T-REX)	☒ Existing	☒ To be used without any modification
[Part 1 of experiment/ equipment]	☐ Existing	☐ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[Part 2 of experiment/ equipment]	☐ Existing	☐ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[insert lines if needed]		

HAZARDS GENERATED BY THE EXPERIMENT (if using fixed installation:) Hazards named in the document relevant for the fixed [MINIBALL + only CD, MINIBALL + T-REX] installation.

Additional hazards:

Hazards	[Part 1 of experiment/ equipment]	[Part 2 of experiment/ equipment]	[Part 3 of experiment/ equipment]
Thermodynamic and fluidic			
Pressure	[pressure][Bar], [volume][l]		
Vacuum			
Temperature	[temperature] [K]		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	[fluid], [pressure][Bar], [volume][l]		
Electrical and electromagnetic			
Electricity	[voltage] [V], [current][A]		
Static electricity			

Magnetic field	[magnetic field] [T]		
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material [material]			
Beam particle type (e, p, ions, etc)			
Beam intensity			
Beam energy			
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☐		
• Open source	☐		
• Sealed source	☐ [ISO standard]		
• Isotope			
• Activity			
Use of activated material:			
• Description	☐		
• Dose rate on contact and in 10 cm distance	[dose][mSV]		
• Isotope			
• Activity			
Non-ionizing radiation			
Laser			
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300 MHz)			
Chemical			
Toxic	[chemical agent], [quantity]		
Harmful	[chem. agent], [quant.]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chem. agent], [quant.]		
Corrosive	[chem. agent], [quant.]		
Irritant	[chem. agent], [quant.]		
Flammable	[chem. agent], [quant.]		
Oxidizing	[chem. agent], [quant.]		
Explosiveness	[chem. agent], [quant.]		
Asphyxiant	[chem. agent], [quant.]		

Dangerous for the environment	[chem. agent], [quant.]		
Mechanical			
Physical impact or mechanical energy (moving parts)	[location]		
Mechanical properties (Sharp, rough, slippery)	[location]		
Vibration	[location]		
Vehicles and Means of Transport	[location]		
Noise			
Frequency	[frequency],[Hz]		
Intensity			
Physical			
Confined spaces	[location]		
High workplaces	[location]		
Access to high workplaces	[location]		
Obstructions in passageways	[location]		
Manual handling	[location]		
Poor ergonomics	[location]		

Hazard identification:

Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): [make a rough estimate of the total power consumption of the additional equipment used in the experiment]: ... kW