EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal
to the ISOLDE and Neutron Time-of-Flight Committee

Study of the Coulomb barrier scattering of ^{10}C with heavy targets

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Requested shifts: 15 shifts.
Beamline: XT03 (SEC)

Abstract

The present proposal aims to investigate the reaction dynamics of the proton-rich nucleus ^{10}C at energies around the Coulomb barrier (Elab= 70 MeV). Previous measurements of the elastic scattering cross sections show an anomalous behaviour that should be investigated in detail. The availability at ISOLDE of intense ^{10}C beams plus the dedicated setup SEC for nuclear reaction studies provide a unique opportunity to perform a high-resolution measurement of elastic and inelastic channels. The collaboration expects to disentangle the reaction dynamics of this exotic proton-rich isotope.

1. Introduction

Nuclear structure has a direct impact on the reaction mechanisms opened at a given relative collision energy. This effect is enhanced in nuclear reactions induced by radioactive nuclei, due to the extreme Z/N ratios and reduced binding energies, like in the case of halo nuclei. At collision energies around the Coulomb barrier, the relative velocity is large enough to have a significant overlap between the tails of the mass distributions around the distance of closest approach, and sufficiently low to provide the time need to excite collective degrees of freedom, thus increasing the coupling between the elastic and inelastic, breakup, transfer, and fusion channels. From the experimental point of view, the most intense channel at these energies is the elastic scattering cross sections. Its angular distribution is by itself a very valuable quantity, as it can provide a first insight into subjacent details of the dynamics of the system, such as the total reaction cross section and the tail of the folded mass distributions. A typical feature of the elastic channel is the appearance of a pronounced increase in the angular distribution of the ratio between measured and Rutherford values, in the vicinity of grazing angle, the so-called Coulomb rainbow, followed by a sharp decrease. An example for the system ^{20}Ne + ^{208}Pb [1] is shown in Figure 1 (left). The shape of the angular distribution can be described in terms of the subjacent reaction channels by means of coupled reaction channel calculations [2], which correlate the angular distribution of the cross sections with nuclear properties such as nuclear shapes, electromagnetic moments, transition probabilities, level energies and spectroscopic factors, among others. These theoretical tools have been thoroughly developed along the last decades using reactions induced by stable nuclei.

In the case of exotic nuclei, the reaction dynamics at energies around the Coulomb barrier is still largely unknown. Our collaboration has studied the interplay between elastic and reaction channels for the scattering of neutron-halo nuclei ^{6,8}He and ^{11}Li. The experiments demonstrated that the weak binding of the system produces a partial decoupling of the valence nucleons from the core, which leads to long range reaction mechanisms and a drastic increase of the reaction cross section, as compared to the scattering of stable isotopes. The dynamics is dominated by nucleon transfer to the continuum and breakup, and the Coulomb rainbow disappears. The case for ^{6}He + ^{208}Pb scattering [3] is shown in Fig. 1 (right). An overall interpretation of the experimental results can be achieved in terms of Optical Model (OM), Coupled Channel (CC), Coupled Reaction Channel (CRC) calculations [3, 4], but the detailed description of the angular and energy distributions of reaction fragments requires the development of dedicated four- body models [5], which altogether are used to probe our understanding of the reaction dynamics of exotic nuclei.

2. Physics case

For proton-halo candidates such as ^{8}B or ^{17}Ne the experimental information at Coulomb barrier energies is sparse and the nature of the reaction mechanisms still rather ununderstood. The Coulomb barrier scattering of ^{8}B with light and heavy targets has been measured with high angular and energy resolution at ISOLDE, using the GLORIA detector [6] system at SEC. The elastic cross section is shown in Fig. 2 (left) [7]. Due to the low proton breakup threshold of only 138 keV, one should expect the dynamics to look like that of the neutron halo ^{11}Be.

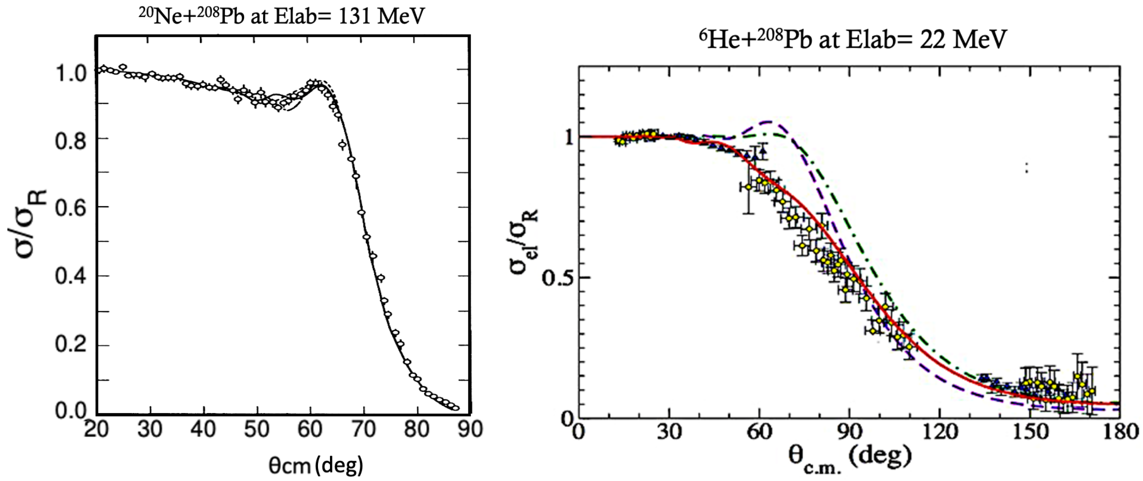

Figure 1. Ratio of the elastic scattering to the Rutherford cross sections, for the scattering system ^{20}Ne+^{208}Pb at Elab= 131 MeV [2] (left panel) and ^{6}He+^{208}Pb at Elab= 22 MeV [3] (right panel). The lines correspond to various theoretical calculations.

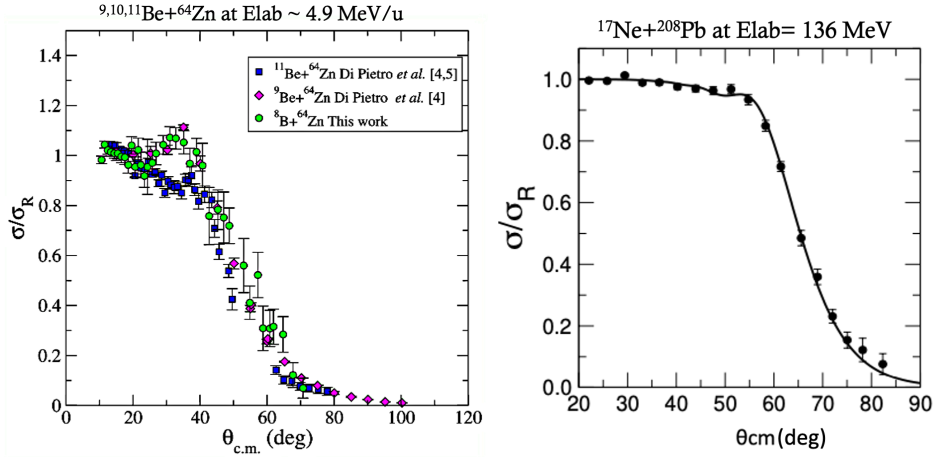

Figure 2. Ratio of the elastic scattering to the Rutherford cross sections, for the scattering systems ^{8}B (proton halo), ^{11}Be (neutron halo) and ^{9}Be (stable) with ^{64}Zn [6] at Elab ~ 4.9 MeV/u (left panel) and ^{17}Ne+^{208}Pb at Elab= 136 MeV [9] (right panel) at Coulomb barrier energies.

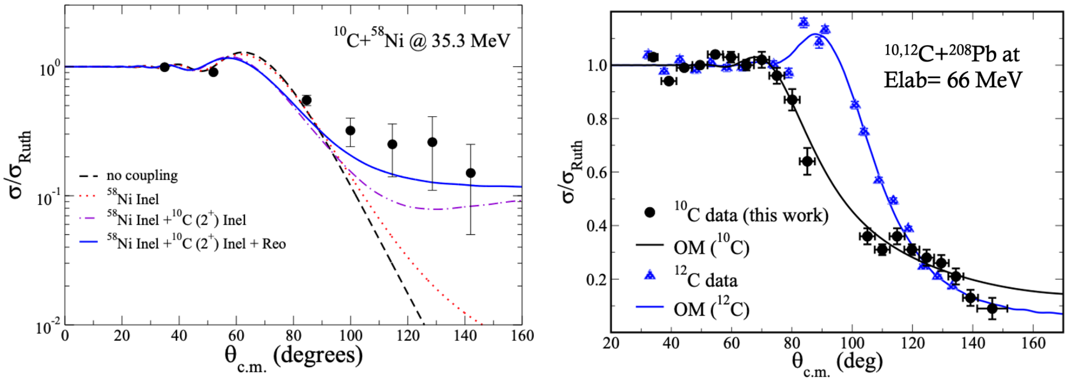

Figure 3. Ratio of the elastic scattering to the Rutherford cross sections, for the scattering system ^{10}C + ^{58}Ni [11] at Elab= 35.3 MeV (left panel) and ^{10,12}C + ^{208}Pb [12] (right panel) at Elab= 66 MeV. The lines correspond to various theoretical calculations.

However, the experiment shows that the elastic scattering angular distributions and the total reaction cross sections are almost identical to that of the stable isotope ^{9}Be, including the presence of the sharp Coulomb rainbow. The subjacent reaction mechanisms are still to be unveiled, and different possibilities are being investigated, such as the effect due to the increase of the effective binding energy [8], or perhaps a possible "core-shading" effect [7].

On the other hand, the dynamics of the proton-halo ^{17}Ne at Coulomb barrier energies was recently studied by our collaboration at GANIL, where the cross sections for the elastic channel and the core fragment ^{15}O were measured with the GLORIA detector system [9]. The results for the elastic channel are shown in Fig. 2 (right). Contrary to the case of ^{8}B, and despite having a much higher proton separation energy, the Coulomb rainbow in the scattering system ^{17}Ne+^{208}Pb is absent, suggesting the presence of long-range reaction mechanisms similar to the case of ^{6}He+^{208}Pb. This feature could be also related to the two-proton halo component in the ^{17}Ne gs wave-function. However, this picture is not consistent with the extracted reaction cross section, which is almost identical to the scattering of stable nuclei ^{20}Ne + ^{208}Pb. This is an extraordinary result, considering that ^{17}Ne is a dripline nucleus.

To achieve a complete understanding of the reaction dynamics of proton rich nuclei at Coulomb barrier energies more experimental data is needed. In this proposal we aim to extend these studies at ISOLDE using the exotic isotope ^{10}C, as the experiments can profit from the existing experimental setup GLORIA+SEC and the high intensity beams available of $7x10^{5}$ pps/μC [10].

Having relatively large single- and double- proton separation energies S_{p}= 4006.8 keV, S_{2p}=3820.94, the proton-rich isotope ^{10}C is not expected to exhibit a proton halo like the ^{8}B and ^{17}Ne isotopes. Its interest resides on its large proton-excess Z/A similar as ^{8}B and ^{17}Ne, the Borromean structure, and the presence of a low energy bound excited state (Ex= 3353.7 KeV). This makes ^{10}C an ideal test-bench to investigate coupling effects and reaction dynamics of proton-rich nuclei at Coulomb barrier energies.

The scattering of ^{10}C at Coulomb barrier energies has been previously measured at the TwinSol facility (NSL, University of Notre Dame, USA) using ^{58}Ni [11] and ^{208}Pb [12] targets. The experiments were not able to separate the excited state from the elastic, and the yields of reaction fragments were not measured. Nonetheless, the angular distribution of the quasi-elastic cross sections could be obtained, and they are shown Figure 3. It is noticeable the absence of the Coulomb rainbow in ^{10}C scattering as compared with stable ^{12}C (blue points in Fig. 3), a surprising feature as the rainbow is clearly present at scattering energies well above the barrier (see e.g., Ref. [13]) and indeed, the angular distributions ^{10,11,12}C on ^{208}Pb are very similar. Thus, data of Ref. [11, 12] should exhibit a pronounced rainbow, and its absence suggests the existence of specific reaction channels opening at Coulomb barrier energies that should further investigated. The coupled channel calculations showed the relevance of reorientation and inelastic contributions, and other channels such as transfer and/or breakup reactions but couldn't be measured.

To solve the ^{10}C dynamics puzzle and gain a very important understanding on the reaction dynamics of proton-rich nuclei, we propose to do a high-resolution measurement of the system ^{10}C + ^{208}Pb at 70 MeV, just around the Coulomb barrier, using the GLORIA+SEC setup at ISOLDE. The quantities to be measured will be:

1. Angular distribution of the elastic cross section
2. Angular distribution of the inelastic cross section
3. Angular distribution of the neutron pick-up cross section

The data will be analysed using coupled channel calculations (FRESCO), and four-body reaction models.

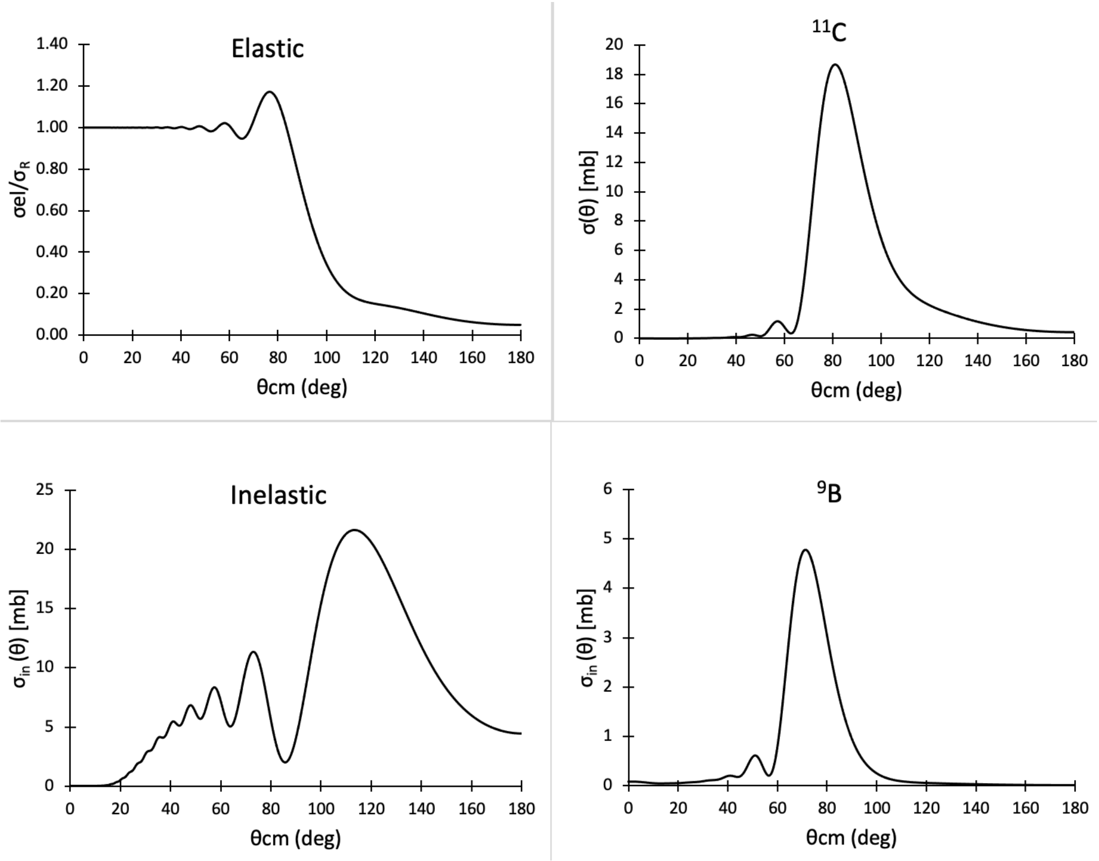

Figure 4. Results of CRC calculations for elastic (a), inelastic (b), neutron pickup (c) and neutron stripping for the system ^{10}C+^{208}Pb at E = 70 MeV.

3. Theoretical calculations

Figure 4 shows the results of CRC calculations for the system ^{10}C + ^{208}Pb at Elab= 70 MeV [14], which reproduces the angular distribution of the elastic cross section measured in [12] at E_{lab} = 66 MeV. The elastic angular distribution is depicted in Fig. 4a, showing the expected Coulomb rainbow. The calculations also predict the angular distribution of the cross sections for inelastic excitation of ^{10}C* to the level at Ex = 3353.7 keV (Fig. 4b), the cross section for neutron pickup to ^{11}C (Fig. 4c), and the production of ^{9}B (Fig. 4d) which is unbound and will decay into 2α+ p. The excitation of ^{208}Pb to the first level at Ex = 2614.5 keV (not shown) might contribute to the reaction process but can be easily separated the ^{10}C* excited state in the particle energy spectra. According to the calculations, the detector setup should cover the angular region around 80° for measuring the Coulomb rainbow, the 90° region to tackle ^{11}C production, and the region around 80° and 140° for the inelastic channel. Cross sections for the non-elastic channels are reasonably large in the range of 10 - 20 mb. As compared with previous measurements, the proposed experiment will benefit from the use of the GLORIA array detector [6], which is optimized to cover the angular region around 90°. Finally, it is worth to mention that although there is no intention to measure the decay of ^{9}B (it would require a dedicated setup), we will obtain yield information for planning future experiments on reaction dynamics, but also for astrophysics [15], and clustering [16] studies.

4. Experimental setup

The goal of the experiment is to determine the cross sections for the elastic and inelastic channels, and the production of ^{11}C for the reaction ^{10}C+^{208}Pb at Elab = 70 MeV. We will use the GLORIA particle detector, an array 6 particle telescopes which for this experiment will be each composed of a thin DE – DSSSD *16 x 16 strips, 40μ thickness) and thick E detector (PAD, 500 μm) (See Ref. [6]). GLORIA will be placed in the SEC reaction chamber (similar to previous INTC-P-278 setup for ^{8}B+^{64}Zn), the central telescopes (around 90°) at 35 mm from a 1.1 mg/cm^{2} reaction target tilted 30°. The setup will cover the relevant regions elastic channel between 20° - 160°, the inelastic between 60°-160°, and the ^{11}C production between 70°-110°. The angular resolution is ~± 2.5° per measured angle, average solid angle ~ 200 msr around 90°.

5. Beam requirements

The beam time request is summarized in Table 1. The number of 14 shifts is estimated from the production yield of 7 x 10^{5} pps/μC [10] (nanostructured CaO) to achieve below 10% uncertainty of elastic, inelastic and ^{11}C production channels in the angular range of interest, assuming a 5% beam transmission between production and reaction target at SEC. One shift of stable ^{12}C (~ 10^{6} pps) is requested for detector set up and calibration.

ISOTOPE	Intensity on target	SHIFTS
^{10}C	3.5x10^{4} pps	14
^{12}C	10^{6} pps	1
	Total	15

Table 1. Beam time request.

6. Safety

No special requirement.

7. Summary of requested shifts

Radioactive beam: 14 shifts of ^{10}C

Stable beam: 1 shift of ^{12}C

References:

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[12] R. Linares et al., Physical Review C 103, 044613 (2021).

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: *The experimental setup comprises: ISOLDE solenoidal spectrometer)*

Part of the Choose an item.	Availability	Design and manufacturing
GLORIA detector system	☒ Existing	☐ To be used without any modification ☒ To be modified: detectors closer to target
SEC reaction chamber	☒ Existing	☒ To be used without any modification ☐ To be modified

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 the experiment/equipment]*	*[Part 2 of the experiment/equipment]*	*[Part 3 of the experiment/equipment]*
Thermodynamic and fluidic			
Pressure			
Vacuum			
Temperature			
Heat transfer			
Thermal properties of materials			
Cryogenic fluid			
Electrical and electromagnetic			
Electricity			
Static electricity			
Magnetic field			
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material	Pb (Lead)		
Beam particle type (e, p, ions, etc)	Ions// 10C, 12C		
Beam intensity (on target)	^{12}C, 10^6 pps ^{10}C, 3.5×10^4 pps		
Beam energy	70 MeV		
Cooling liquids			
Gases			
Calibration sources:	☐		
• Open source	☒ Alphas -callibration		
• Sealed source	☐ [ISO standard]		
• Isotope			
• Activity			
Use of activated material:			
• Description	☐		

• Dose rate on contact and in 10 cm distance	[		
• Isotope			
• Activity			
Non-ionizing radiation			
Laser			
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300MHz)			
Chemical			
Toxic	[chemical agent], [quantity]		
Harmful	[chemical agent], [quantity]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chemical agent], [quantity]		
Corrosive	[chemical agent], [quantity]		
Irritant	[chemical agent], [quantity]		
Flammable			
Oxidizing			
Explosiveness			
Asphyxiant			
Dangerous for the environment	[chemical agent], [quantity]		
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]		

0.1 Hazard identification

3.2 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)*

10 kW