EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Fusion hindrance at sub-barrier energies for weakly bound nuclei on heavy targets: the ^{8}B + ^{208}Pb case

May 18, 2017

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CERN-INTC-2017-037 / INTC-P-508
18/05/2017

Abstract:

We propose a study of the ^{8}B + ^{208}Pb system at the sub-Coulomb energy of 43 MeV via measurements of the elastic scattering and ^{7}Be production cross sections. The main goal of this work is to answer a fundamental question concerning the competition between fusion and direct channels below the barrier for a proton halo nucleus like ^{8}B incident on a heavy target. It is believed from phenomenological predictions that for weakly bound nuclei incident on heavy targets the direct channels exhaust most of the total reaction cross section for incident energies below the Coulomb barrier, with important consequences for both fusion and various astrophysical problems. In this context the sub-barrier breakup and elastic scattering will be investigated for a global understanding of this issue and the relevant channel coupling effects. In addition the elastic scattering measurement will address another fundamental question: how far does the elastic scattering for proton halo nuclei deviate from Rutherford scattering at energies below the barrier? The measurement will include angular distributions of both the elastically scattered ^{8}B nuclei and the ^{7}Be breakup fragments by using the GLORIA multiarray. The breakup measurement will be performed in inclusive mode due to the low beam flux, via the measurement of the ^{7}Be - production. These nuclei can be produced as breakup fragments and as reaction products of a p - transfer process. The latter is, however, expected to occur with a very low probability, while the total ^{7}Be production includes all direct processes, the determination of which is the main goal of this study.

Requested shifts: 21 shifts - 7 days
Installation: 2nd beamline of HIE-ISOLDE

1 Scientific Motivation

This proposal, which includes an elastic scattering and a breakup measurement, is mainly motivated by a sound result reported in Ref. [1] for the fusion hindrance of weakly bound nuclei on heavy targets starting at energies just below barrier. This conclusion was obtained using systematic results for fusion and total reaction cross sections and mapping the energy dependence for the ratio of direct to total reaction cross section at near and sub-barrier energies (see Fig. 1). It was found that while at near but above -barrier energies this ratio is similar for weakly bound nuclei on all targets, close to $\sim$ 20%, for energies below the barrier and only for heavy targets this ratio increases up to $\sim$ 100 %, leaving little room for fusion. If this prediction can be validated experimentally it will have important consequences for the fusion mechanism itself and for various astrophysical problems. So far it has only been verified above the barrier because the cross sections are usually very small at sub-barrier energies and therefore very difficult to measure sufficiently accurately. ^{8}B, a proton rich nucleus with a possible proton halo, gives us a unique possibility to obtain the direct part of the total reaction cross section at energies below the barrier. According to Continuum Discretized Coupled Channels (CDCC) calculations, breakup seems to exhaust most of the total reaction cross section, presenting at the sub-barrier energy of 43 MeV the rather large cross section of $\sigma_{\text{breakup}} = 360$ mb in comparison with a total reaction cross section of $\sigma_{\text{tot}} = 415$ mb. Calculated elastic

scattering and breakup angular distributions are shown in Figs. 2 and 3. As may be seen from Fig. 3, the breakup cross section is concentrated in a very narrow angular range at forward angles and therefore should be easily accessible in an angular distribution measurement. It should be noted that the subject of fusion hindrance for stable heavy-ions has been reported and debated in several articles in the past but for extreme sub-barrier energies [2, 3, 4, 5]. The only existing measurements for the fusion ^{8}B on ^{58}Ni [6] present a large enhancement below and above barrier contradicting results above barrier for ^{8}B fusion on ^{28}Si [7].
Furthermore, elastic scattering of exotic nuclei has proved to be a powerful tool for investigating channel coupling mechanisms, especially at near-barrier energies [8]. Standard methods, usually within a CDCC approach for weakly bound projectiles, have been developed to study near-barrier elastic scattering and its associated direct reactions within the coupled-channels technique. In these investigations strong couplings to direct channels do not always seem to be directly connected with the observation of large breakup or transfer reaction cross sections. Specifically, in Ref. [9] the authors investigate breakup coupling effects on near-barrier ^{6}Li, ^{7}Be and ^{8}B + ^{58}Ni elastic scattering in a CDCC approach. They observe the following paradox: ^{6}Li, with a relatively small breakup cross section, exhibits an important breakup coupling effect on the elastic scattering, whereas ^{8}B, with a large breakup cross section, shows a very modest coupling effect. Further investigation found that the coupling effect on the modulus of the S matrix, which is connected with changes in the imaginary part of the potential, is almost negligible for ^{8}B and largest for ^{6}Li. By contrast, for arg(S), which is connected with changes to the real part of the potential, the coupling effect is greatest for ^{8}B, smallest for ^{7}Be and intermediate for ^{6}Li. The same problem is reported in the literature in an alternative approach, related to the effect of Coulomb or/and nuclear couplings as a source of Coulomb rainbow suppression [10] or as a deviation from Rutherford scattering at energies below the barrier [11]. Each case investigated appears to be unique. In this respect large effects concerning the disappearance of the Coulomb rainbow are observed for ^{6}He on heavy targets and calculations confirm [12] that they are mostly due to Coulomb dipole couplings. For ^{11}Be the effect persists for medium mass targets and the origin of the phenomenon seems to be different, in that nuclear couplings are much more important here [9, 13]. With respect to deviations from Rutherford scattering at very low energies, measurements at near-barrier energies for ^{6}He show slight deviations, while well below the barrier the only existing measurement for ^{11}Li+^{208}Pb exhibits the persistence of a dramatic deviation from Rutherford scattering [11]. The reduction is confirmed in four-body continuum-discretized coupled channel calculations based on a three-body model of the ^{11}Li projectile and is attributed to the strong Coulomb dipole coupling to the the low-lying continuum of ^{11}Li.
Motivated by the above considerations, we propose an elastic scattering measurement for the ^{8}B + ^{208}Pb system at the sub-Coulomb energy of $E_{^{8}\mathrm{B}} = 43$ MeV with a simultaneous measurement of the ^{7}Be production. According to our calculations [9] a rather moderate deviation from Rutherford scattering is predicted for this system, as may be seen from Fig. 1, but this needs to be verified experimentally. As was already said the rather large ^{7}Be production yield is expected to come mainly from the elastic breakup and with a very low probability from a p - transfer process. This was verified previously in a ^{8}B + ^{58}Ni measurement [14]. Moreover, breakup and p - transfer are the only direct open

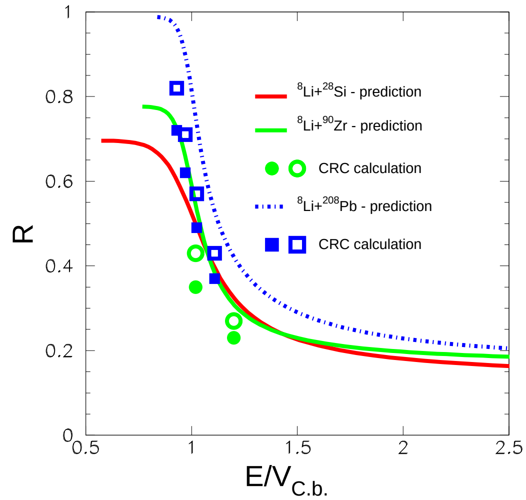

Figure 1: Ratio direct to total reaction cross section for ^{8}Li on various targets. Similar results can be obtained for ^{8}B- from Ref. [1].

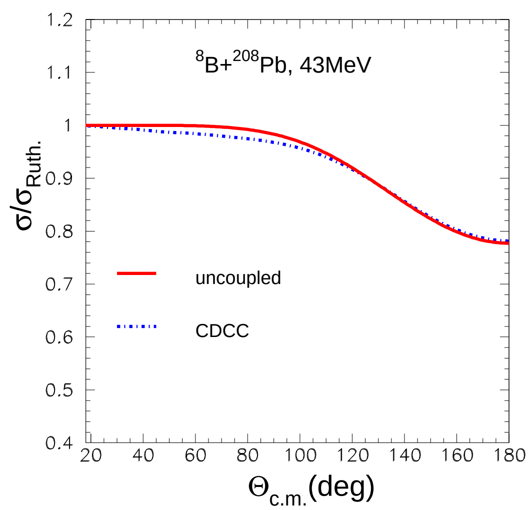

Figure 2: Elastic scattering calculations in a CDCC approach for ^{8}B + ^{208}Pb [8].

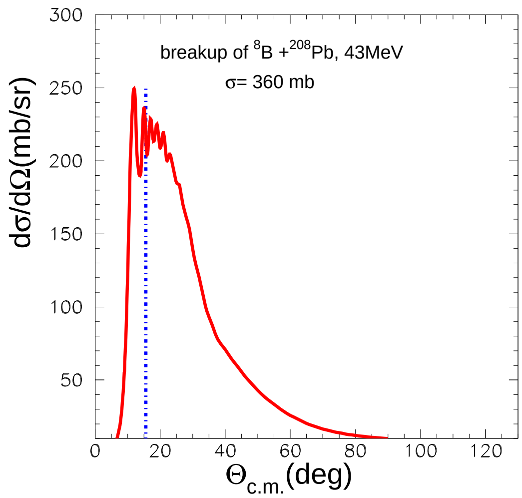

Figure 3: Calculated breakup cross sections in a CDCC approach [8]. The vertical dot-dashed blue line denotes the lower point up to which we can measure the breakup with our setup.

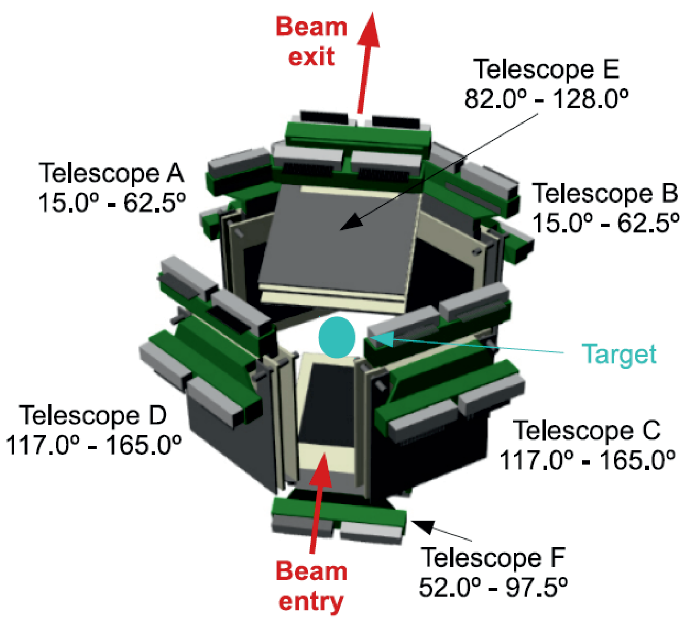

Figure 4: 3D representation of our setup, the GLORIA array [15]. Relative positions of the detectors are indicated in the figure.

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channels in this energy, therefore the determination of ^{7}Be - production will determine all the direct part of cross section, which is the main goal of this study.

2 Proposed Experiment

The proposed experiment is well suited for a beam with a low flux such as the ^{8}B beam at REX-ISOLDE. It is of particular interest due to the importance of ^{8}B in astrophysical and reaction mechanism problems, especially at near-barrier energies. To date low-energy beams of ^{8}B have been produced by the in flight technique and are therefore of low quality. The availability of a post accelerated beam at REX-ISOLDE will give us the possibility to obtain high quality data with a strong impact in our community. The proposed experiment includes angular distribution measurements of both the elastically scattered ^{8}B and the ^{7}Be-particle production. Our experimental set up, schematically presented in Fig. 4, will include six two-stage telescopes, 40μm DSSSD + 1500 μm thick DSSSD detectors from the GLObal Reaction Array (GLORIA) [15]. The telescopes will be set at a distance of $\sim$ 6 cm from the target in a compact geometry, as illustrated in Fig. 4, at positions so as to cover the angular range between 15° and 165°. The exact position of each telescope is indicated in Fig. 4. The most forward telescopes (A and B) will be set at symmetrical positions for testing divergence of the beam, accurately determining the beam flux and determining the breakup cross section with good statistical accuracy, covering most of the angular range of the breakup fragments (see Fig. 3). The other telescopes will cover most of the angular range of the elastically scattered ^{8}B. A 1.5 mg/cm^2 thick target will be set in the middle of the chamber tilted by 25° with respect to the z-axis in order to avoid the shadow of the target holder in the angular range around 90°.
Summary of requested shifts: Taking into account a mean secondary beam intensity of 5×10^3 pps, a lead target thickness of 1.5 mg/cm^2, the differential cross section for elastic scattering and breakup appearing in Figs. 2 and 3 respectively, and a solid angle per strip ($\Delta\theta_{\rm lab} \sim 3.0°$) of $\sim 4.4 \times 10^{-2}$ sr, we request **17 shifts**. Within this beam time schedule we intend to obtain differential cross sections for elastic scattering with a statistical error of less than 1% for angles below 38° while for critical angles such as those at $\theta = 90°$ we will obtain cross sections with an error of $\sim$ 7%, at $\theta = 130°$ with an error of 12% and at $\theta = 160°$ an error of 15%, the last two dropping down to 8% and 10% respectively if we take into account a weighted mean between the two symmetrical detectors. For the breakup measurement at the most prominent angles, 15° to 29°, where the differential cross section is between 230 to 150 mb/sr the statistical error will be between 10% to 12% respectively (the collected counts will be 110 to 70 between 15° and 29°). To the right of the peak, at 47° the error will be 21% for 23 counts in total ($\sigma(\theta)$ = 50 mb/sr). These uncertainties could be reduced to 7%, 8.5% and 15% correspondingly, if we take into account a weighted mean between data from the two symmetrical detectors. **Four additional shifts** are requested for delivering the beam and for tuning the electronics. Therefore, in total we request **21 shifts** corresponding to $\sim$ 7 days

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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
(General purpose reaction chamber HIE-ISOLDE 3rd beam line, XT03)	☒ Existing	☒ To be used without any modification
Silicon detector system GLORIA [*]	☒ 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
	☐ 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]		

* G. Marquinez-Duran, et al. ”GLORIA: A compact detector system for studying heavy ion reactions using radioactive beams”. Nuclear Instruments and Methods in Physics Research Section A 755 (2014) 69-77.

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			
Vacuum	10^{-6} mbar		
Temperature	Room temperature		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid			
Electrical and electromagnetic			
Electricity			

Static electricity			
Magnetic field			
Batteries			
Capacitors			
Ionizing radiation			
Target material [material]	^{208}Pb, 1.5 mg/cm^2		
Beam particle type (e, p, ions, etc)	^{8}B		
Beam intensity	10^3 - 10^7		
Beam energy	5.38 MeV/u		
Cooling liquids			
Gases			
Calibration sources:	☒		
• Open source	☒		
• Sealed source			
• Isotope	Am,Pu,Cm		
• Activity	1 kBq		
Use of activated material:	NO		
• Description			
• Dose rate on contact and in 10 cm distance			
• 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	Bat. 170, 1 Rack for electronics and dacq		
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]: 20 kW