EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Determination of the α decay width of a near-threshold proton-emitting resonance in ^{11}B

May 11, 2022

Y. Ayyad[1], W. Mittig[2,3], B. Olaizola[4], H. Alvarez-Pol[1], D. Bazin[2,3], S. Beceiro-Novo[3], M. Caamaño[1], J. Chen[5], B. Fernández-Domínguez[1], S.J. Freeman[6], J. Surbrook[2,3], J. C. Zamora[2], V. Zelevinsky[2,3]

[1]*IGFAE, Universidade de Santiago de Compostela, E-15782, Santiago de Compostela, Spain*
[2]*Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI 48824, USA*
[3] *Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[4]*ISOLDE-EP, CERN, CH-1211 Geneva 23, Switzerland*
[5] *Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA*
[6] *School of Physics and Astronomy, University of Manchester, Manchester M13 9PL, UK*

Spokesperson: Y. Ayyad (ayyadlim@nscl.msu.edu)
Co-spokesperson: W. Mittig (mittig@nscl.msu.edu)
Contact person: B. Olaizola (bruno.olaizola@cern.ch)

Abstract: We propose to measure directly the partial width for α emission of the controversial near-proton-threshold narrow resonance of ^{11}B at 11.425 MeV. This partial width is of capital importance to address the large β-delayed proton emission branching ratio of ^{11}Be populating such state. The measurement will be performed using resonance proton scattering in inverse kinematics using the thick target technique and a 300 keV/u ^{10}Be beam.

Requested shifts: 8 shifts
Installation: Travelling setup installed at XT-03

The existence of resonances near particle decay thresholds is a universal phenomenon in nuclei. The most representative case of these resonances is the famous ^{12}C 0^+ Hoyle state which explains the production of carbon in stars via the triple-alpha process [1]. In general, the physics of α-clusterization in nuclei is not well understood in spite of its great importance for many problems. Besides the well-known α-clustering , there are other examples of near threshold resonances where the system is formed by one or two nucleons and the core, i.e. ^{11}Li (^{9}Li(g.s.)$\otimes$ 2n), ^{15}F (^{13}N$\otimes$2p), and more recently ^{11}B (^{10}Be$\otimes$ p and ^{10}B $\otimes$ n) [2]. The appearance of these narrow resonances can be attributed to the interplay between internal structure and reaction mechanisms that enable near-threshold collectivity [3]. Generally, resonances are one of the most important ingredients in our understanding of nuclear structure and also in reactions of astrophysical interest that occur at very low energies.

Recently, a narrow near-threshold resonance in ^{11}B was inferred from the β^--delayed proton emission in ^{11}Be [2] in an experiment performed by our collaboration, Active Target Time Projection Chamber (AT-TPC) group. This type of decay seems, *a priori*, not natural in a neutron-rich nuclei. However, if the neutron separation energy is below $S_n < 782$ keV, the decay is energetically allowed. This condition is fulfilled in a few selected halo nuclei and the decay of the halo neutron can be considered as quasifree [4]. The experiment, performed with the prototype Active Target Time Projection Chamber (pAT-TPC), provided the first direct observation of low energy protons from ^{11}Be ($Q_{\beta p}$ is around 280 keV). The energy spectrum determined in this experiment features a very narrow distribution (around 15 keV), centered at around 180 keV. The inferred branching ratio is 1.3×10^{-5}, in good agreement with a previous indirect measurement where only the ^{10}Be was identified [4]. This branching ratio is many orders of magnitude larger than what theoretical calculations predict for a quasifree neutron decay [5]. Two possible explanations were proposed to solve this conundrum: The decay could populate a previously unobserved resonance in ^{11}B, changing the available phase space and enhancing the decay or, there could be unaccounted additional decay channels contributing to the decay. The former reason is the most plausible as inferred from the energy spectrum obtained in the experiment which suggests that ^{11}Be undergoes β-decay through a narrow resonance in ^{11}B located at $E = 11425$ keV, with $J^\pi = (1/2^+, 3/2^+)$, an spectroscopic factor of 0.5 and a width of around 15 keV.

In order to clarify the existence and the properties of this exotic resonance in ^{11}B, we conducted an experiment to measure the resonance proton elastic scattering on ^{10}Be in inverse kinematics [6]. The experiment was performed using a reaccelerated ^{10}Be beam at 350 keV/u provided by the ReA3 accelerator of the Facility for Rare Isotope Beams. The excitation function, shown in the right panel of Fig. 1, clearly features the typical pattern of the interference between a narrow resonance and potential scattering. An R-matrix fit with the AZURE2 code was performed to infer the properties of the resonance. The results, in very good agreement with the ones inferred from the β-decay of ^{11}Be, are $E_R = 171 \pm 20$ keV ($E_x = 11.4$ MeV), $J^\pi = 1/2^+$ and $\Gamma_p = 4.4$ keV. One of the most interesting features is the partial width for proton emission that indicates a strong branching ratio to the α decay channel. Unfortunately, due to the very low beam intensity (around 1000 pps) we had during the experiment, it was not possible to directly observe it. A structure can be observed in the excitation function for the (p,α) channel (see Fig. 2), plagued with the α background of the permanent calibration source we used during the experiment. The inferred partial width for α decay is 11±3 keV. However, the precise determination of this partial width is paramount to assess the controversial β-delayed proton emission branching ratio of ^{11}Be. In the work of Ref. [2] was impossible to identify α particles coming from other broader neighboring states, and therefore, the direct measurement of the ^{11}Be to ^{7}Li+^{4}He from the 11.4 MeV state is impossible with the detection scheme we used (Time Projection Chamber). Moreover, very recent state-of-the-art calculations are still conflicting regarding the ^{11}B structure and the large β-decay proton emission rate [7, 8]. It is important to remark that most of these calculations are based on the properties of the resonance for which, once again, there is only one controversial experimental result. Even though there is a widespread agreement on its existence, there are still fundamental questions that will impact the calculations: α partial width, better determination of resonance energy and width, absence of other resonances within the experimental energy domain. The observation of this peculiar resonance is of capital importance to understand how these near-threshold narrow resonances appear and how this phenomenon impacts the structure of stable and exotic nuclei.

In this experiment we propose to measure directly the ^{10}Be(p,α) reaction at 300 keV/u to determine the partial decay width into ^{7}Li+^{4}He of the 11.4 MeV near-threshold resonance. Simultaneously, we will determine the ^{10}Be(p,p) with better precision. It is worth pointing out that the neutron emission channel is not accessible with this beam energy. We will use the same detection setup we used for the previous experiment, consisting of a Multichannel Plate and Si detectors.

Proposed experiment at ISOLDE

Given the extremely long lifetime of ^{10}Be ($T_{1/2} = 1.5 \cdot 10^{6}$ y), it can be considered stable for all purposes. For this reason, ^{10}Be can be extracted from any UC$_x$ old irradiated target and it is suitable for either the normal proton schedule or the winter physics period. A RILIS scheme is available and it has demonstrated its ability to ionize Be isotopes. The ions will be extracted, mass separated at either separator and then injected at EBIS. The trap will re-accelerate the beam to an energy of 300 keV/A and conduct it to the XT-03 line, to a dedicated setup developed specifically for this experiment. For this purpose, the Scattering Chamber will have to be removed from the beam line, but that has been done already several times in the past.

Since we are searching for a narrow resonance in the vicinity of the proton emission threshold in ^{11}B, the best method is, arguably, resonant proton scattering using the thick target method. We will use exactly the same experimental setup (see Fig. 3) used for the recent ^{10}Be+p experiment. It consists of a transmission Microchannel Plate (MCP) detector coupled to two Si detectors placed at 10 cm in forward direction. We will use an aluminized (few tens of nm) CH$_2$ foil of 10 μm as target. Secondary electrons produced in the aluminum by the beam will be deflected to the Microchannel plate. The setup

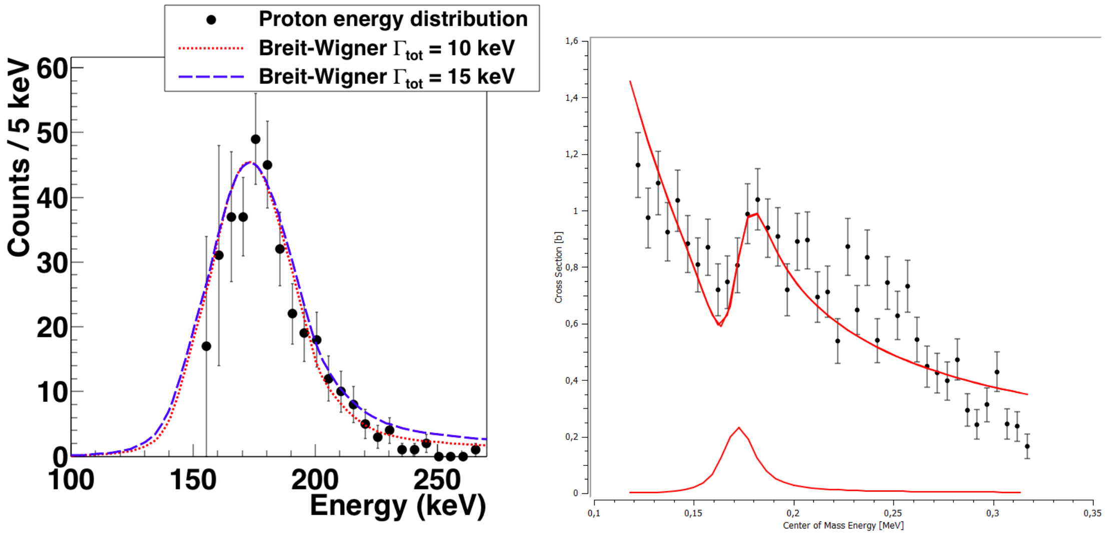

Figure 1: Left panel: Energy distribution of β-delayed protons emitted from ^{11}Be (solid dots) compared to a Breit-Wigner distribution. From Ref. [2]. Right panel: Excitation function for the ^{10}Be+p reaction at 300 keV/u. The solid line refers to R-matrix calculations for both the (p,p) and the (p,α) channels.

mounts directly in any beam line through a ISO-K flange. The MCP signal in coincidence with the Si signal enables particle identification by Time of Flight, as shown in the left panel of Fig. 2. The resolutions, inferred from the previous experiment, amount to few ns and 10 keV (CoM) for the time and energy (Si), respectively. The beam will stop inside the target (around 9 μm range). This enables the measurement at 180 deg (CMS) where the resonant effects are dominating. One of the advantages of performing the experiment in inverse kinematics is that the energy of the α particles from the resonance decay have an energy of about 4000 keV, quite far away from the energy region of the emitted protons. This is illustrated in Fig 2 where the E-ToF (left panel) and the experimental excitation function of the (p,α) reaction (right panel) is shown. The α particle events located between 4 and 6 MeV originated from the use of a ^{228}Th source, that had left a residual activity even after having been removed from the detection chamber. This can be avoided using a different α source, and this background should decrease by orders of magnitude.

Assuming an energy resolution of the Si detector of around 20 keV (5 keV in C.M.), we will obtain energy points in the resonance region for each 0.2 μm of CH$_2$ thickness, corresponding to 1.78$\times$10^{18} hydrogen atoms/cm^2. The calculated and measured cross sections for the (p,p) and (p,α) reactions are of the order of 1 b/sr and 0.2 b/sr (Fig. 1). By placing a Si of around 2 cm of diameter at 10 cm right in front of the target (50 msr), we will have a reaction rate of 2.6$\times$10^{-8}. With an intensity of 10^5 pps we will obtain 2 counts per hour and 5 keV energy bin. We request a total of 6 shifts for the measurement of the reaction, focusing on the (p,α) channel. 2 extra shifts are requested for calibration purposes, if possible, using a proton beam.

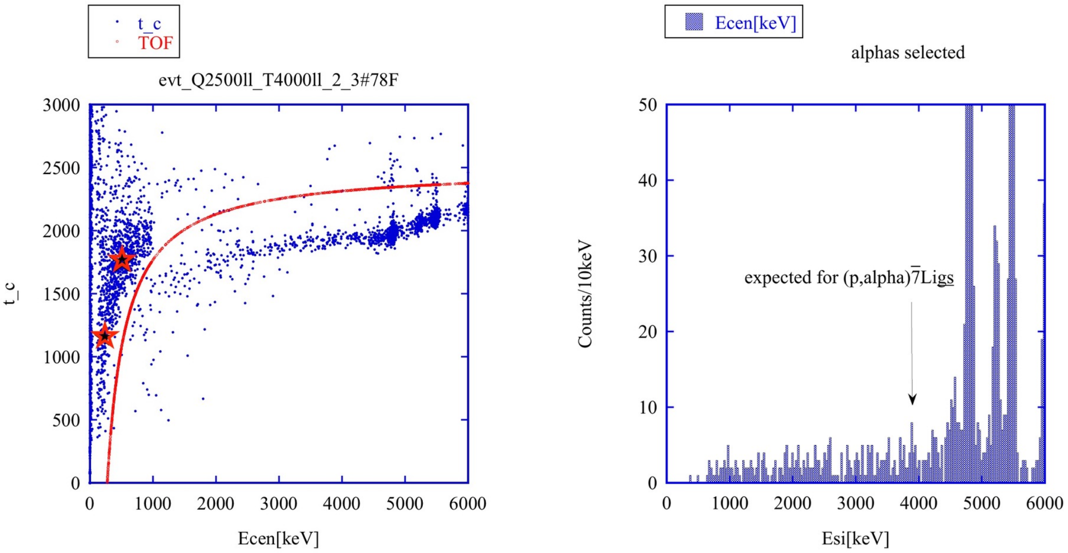

Figure 2: Left panel: Energy vs ToF determined with the Si energy and the ToF between the MCP and the Si. The solid line separates the proton and α ToF lines. Stars refer to the calibration points using a proton beam. Right panel: Excitation function for α particles.

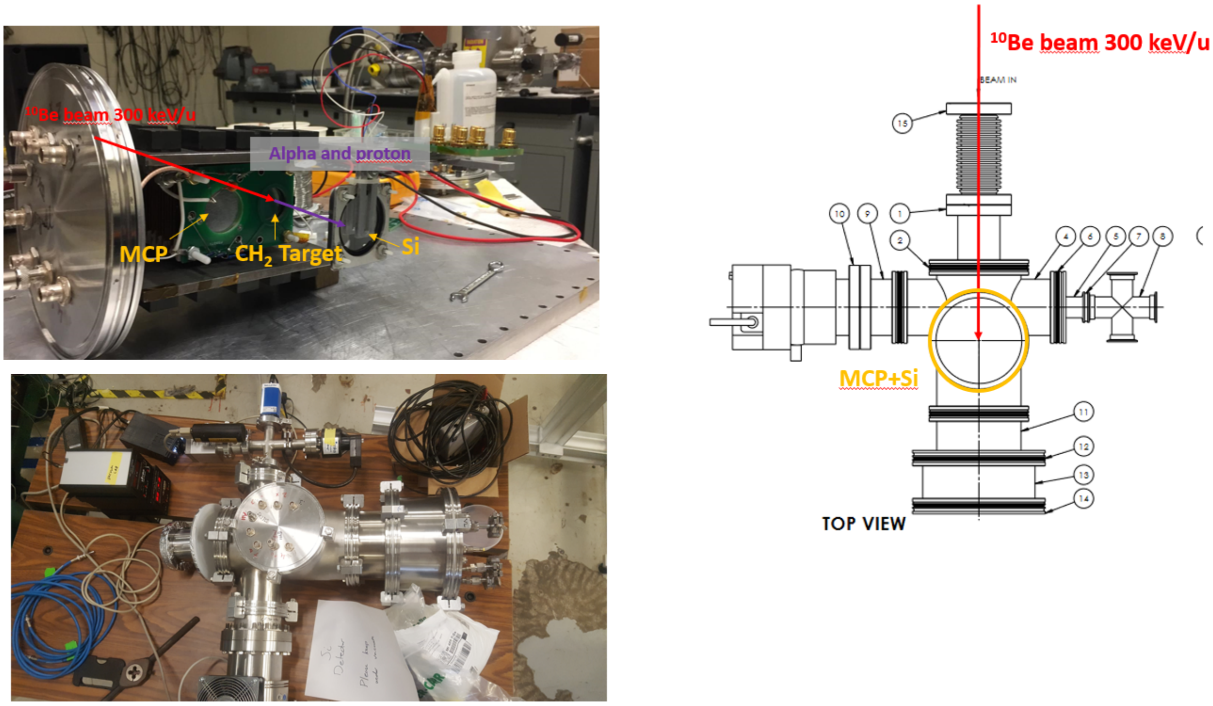

Figure 3: Experimental setup of the proposed experiment.

Possible contaminants could originate from reactions in Carbon in the CH_2 target. We have evaluated the probability using PACE4. Since we are performing this experiment at energies way below the Coulomb barrier, the cross section for fusion-evaporation of protons and alpha particles at zero degrees is around 0.035 mb/sr and 0.4 mb/sr, respectively. This is orders of magnitude lower than the cross sections of the reaction channel of interest.

The beam yield for ^{10}Be has been established at ISOLDE from UC_x target and Ta foils to be of the order of 10^{10} and 10^9 pps, respectively. Assuming a 1% transport efficiency through EBIS, the beam rate would still be orders of magnitude above what our DAQ can process. Therefore, there is ample room to tune EBIS in order to greatly suppress any stable contaminant coming from the trap and still obtain intensities of the order of 10^5 ^{10}Be per second.

Summary of requested shifts: 6 shifts for data taking and 2 for device calibration.

References

[1] M. Freer and H.O.U. Fynbo. The hoyle state in 12c. *Progress in Particle and Nuclear Physics*, 78:1 – 23, 2014.

[2] Y. Ayyad, B. Olaizola, W. Mittig, G. Potel, V. Zelevinsky, M. Horoi, S. Beceiro-Novo, M. Alcorta, C. Andreoiu, T. Ahn, M. Anholm, L. Atar, A. Babu, D. Bazin, N. Bernier, S. S. Bhattacharjee, M. Bowry, R. Caballero-Folch, M. Cortesi, C. Dalitz, E. Dunling, A. B. Garnsworthy, M. Holl, B. Kootte, K. G. Leach, J. S. Randhawa, Y. Saito, C. Santamaria, P. Šiurytė, C. E. Svensson, R. Umashankar, N. Watwood, and D. Yates. Direct observation of proton emission in ^{11}Be. *Phys. Rev. Lett.*, 123:082501, Aug 2019.

[3] J. Okołowicz, M. Płoszajczak, and W. Nazarewicz. Convenient location of a near-threshold proton-emitting resonance in ^{11}B. *Phys. Rev. Lett.*, 2020.

[4] K. Riisager, O. Forstner, M.J.G. Borge, J.A. Briz, M. Carmona-Gallardo, L.M. Fraile, H.O.U. Fynbo, T. Giles, A. Gottberg, A. Heinz, J.G. Johansen, B. Jonson, J. Kurcewicz, M.V. Lund, T. Nilsson, G. Nyman, E. Rapisarda, P. Steier, O. Tengblad, R. Thies, and S.R. Winkler. ^{11}be(βp), a quasi-free neutron decay? *Physics Letters B*, 732:305 – 308, 2014.

[5] D. Baye and E.M. Tursunov. β delayed emission of a proton by a one-neutron halo nucleus. *Physics Letters B*, 696(5):464 – 467, 2011.

[6] Y. Ayyad, W. Mittig, T. Tang, B. Olaizola, G. Potel, N. Rijal, N. Watwood, H. Alvarez-Pol, D. Bazin, M. Caamaño, J. Chen, M. Cortesi, B. Fernández-Domínguez, S. Giraud, P. Gueye, S. Heinitz, R. Jain, B. P. Kay, E. A. Maugeri, B. Monteagudo,

F. Ndayisabye, S. N. Paneru, J. Pereira, E. Rubino, C. Santamaria, D. Schumann, J. Surbrook, L. Wagner, J. C. Zamora, and V. Zelevinsky. Evidence of a near-threshold resonance in ^{11}B relevant to the β-delayed proton emission of ^{11}B, 2022.

[7] J. Okołowicz, M. Płoszajczak, and W. Nazarewicz. Convenient location of a near-threshold proton-emitting resonance in ^{11}B. *Phys. Rev. Lett.*, 124:042502, Jan 2020.

[8] J. Okołowicz, M. Płoszajczak, and W. Nazarewicz. β^{-}p and $\beta^{-}\alpha$ decay of the ^{11}be neutron halo ground state, 2021.

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:) None expected

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