EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Beta decay of ^{11}Be

October 6, 2016

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CERN-INTC-2016-048 / INTC-P-479
06/10/2016

Abstract: The goal of this proposal is to measure the contiunuous spectrum of β-delayed protons emitted in the β^- decay of ^{11}Be. ^{11}Be is to date the only isotope known to decay by β^--delayed proton emission. This measurement would constitute the first direct observation of this rare decay mode. The ^{11}Be beam, postaccelareted with HIE-ISOLDE, will be implanted into the time projection chamber with optical readout developed at the University of Warsaw and there its decay will be observed practically free of background.

Requested shifts: 21 shifts, (split into 1 run over 1 year)
Installation: 2nd beamline

1 Introduction

Beta-delayed proton (βp) emission is a phenomenon that happens typically in very proton rich nuclei, where the Q-value for β decay becomes larger than the particle-separation energy in the daughter nuclei. Close to the proton drip-line it may even become the dominant decay mode and the way in which the β strength is distributed among unbound levels becomes important for these nuclei. Normally, one would expect this decay mode to happen spontaneously only in proton-rich nuclei. Nevertheless, β^--delayed proton ($\beta^- p$) emission from nuclei with a very low neutron-separation energy (S_n) is possible, since $Q_{\beta p}$=782 keV -S_n. These are typically light (halo) nuclei which, over twenty years after their discovery, continue to be a very fertile playground for probing nuclear structure, as their βp decay can proceed through the continuum states in the daughter nucleus.

In this context ^{11}Be is a particularly interesting isotope, being a one-neutron halo nucleus and to date the only nucleus known to decay by β^-p [3]. βp decay from a one-neutron halo nucleus is conceptually similar to β-delayed deuteron (βd) from a two-neutron halo nucleus. Several models are available to describe the properties of the decay

$$^{11}\mathrm{Be} \xrightarrow{\beta^-} {}^{10}\mathrm{Be} + \mathrm{p},$$

predicting both the energy spectrum and the branching ratio for this rare decay mode [1, 2, 3, 4]. The latter spans from $2.5 \cdot 10^{-8}$ to 10^{-6} [5]. The intrinsic clustering of the halo states allows to describe the major part of the wavefunction as factorised into halo part and core, so that the β decay can be seen as the separate decay of the core and halo parts. The βp decay of ^{11}Be can therefore be pictured as the decay of an initial state consisting of an s-wave neutron in the potential given by an inert ^{10}Be to a final state consisting of a continuum wave function of an s-wave proton in the ^{10}Be potential (Coulomb and nuclear). The energy spectrum of βp calculated in this discretized continuum direct decay (DCDD) formalism [1] is shown in Figure 1. All the theoretical models, including DCDD, give a center-of-mass energy for the protons below 200 keV, peaking between 150 and 180 keV. Above 200 keV the phase space is too small and the decay is hindered.

The β-decay properties of ^{11}Be are summarised in Table 1. Of the several β-delayed particle channels that are opened in the decay of ^{11}Be, only β-delayed alpha ($\beta\alpha$) emission was observed directly, with a branching ratio $b_{\beta\alpha}$=3.47(12)% [6]. In the case of βp emission, the low energy expected for the protons on the basis of Q-value considerations and from calculations does not allow for a direct measurement of the emitted protons using standard semiconductor detectors. Instead, indirect observation of βp was obtained by measuring the amount of ^{10}B decay daughter with accelerator mass spectrometry and the branching ratio $b_{\beta p}$=$8.3(9) \cdot 10^{-6}$ was deduced [3]. The latter is surprisingly large with respect to the value expected from calculations and within the current models it can be explained only if the decay proceeds through a new single-particle resonance in ^{11}B strongly fed in β decay [3]. The B(GT) value could be as high as 3, which can correspond to the free neutron decay, as would be when the halo neutron decays into a single-proton state. The measurement of the βp energy spectrum becomes therefore mandatory in order to estimate the Gamow-Teller strength distribution and provide a test of the calculations to show whether the hypothesis of a direct relation between βp decay mode and halo structure is correct.

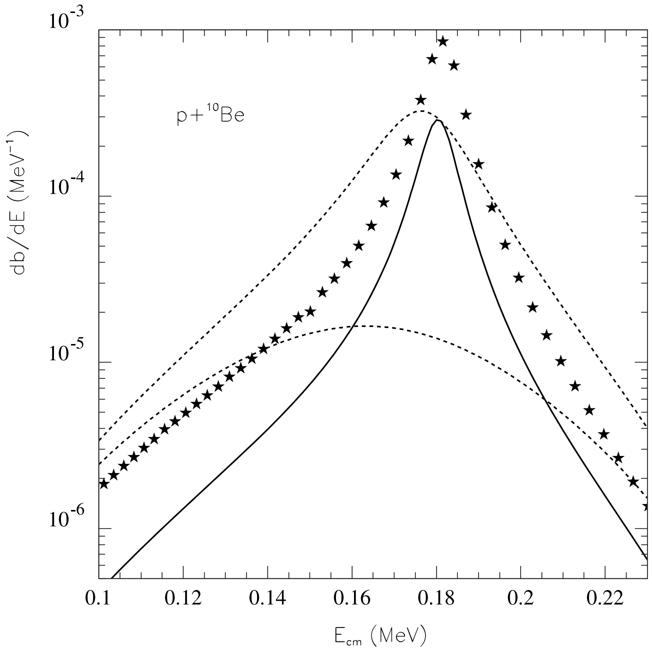

Figure 1: Energy spectrum predicted for decays into p+^{10}Be as a function of centre-of-mass energy [1]. Results of discretized continuum direct decay model calculations with square well potentials are plotted as stars. The solid curve are results from an R-matrix calculation, the dashed curves arise from allowing the alpha decay of the level with widths of 0 keV and 100 keV. See Ref. [1] for details.

It is interesting to note that β-delayed tritium (βt) emission is also possible, with a Q value similar to that for βp (see Table 1), although the probability for this decay mode should be lower because of the one-neutron halo structure of ^{11}Be.
The goal of the measurement proposed here is to reinvestigate the β decay of ^{11}Be and provide the first direct observation of its βp decay. The βp branching ratio will be verified and the energy spectrum measured. The βp branching ratio will be determined with respect to b$_{\beta\alpha}$, the absolute value of which will be remeasured with the same technique in a separate experiment elsewhere.

2 Experimental set-up

In order to detect the βp emitted by ^{11}Be, the Optical Time Projection Chamber (OTPC) developed at the University of Warsaw [8, 9] will be coupled to the HIE-ISOLDE facility. The ^{11}Be beam will be produced at ISOLDE by the 1 GeV proton beam impinging on a UC$_x$ target, ionised in RILIS, separated in the GPS, post-accelerated and implanted into the active volume of the detector. Key characteristic of the HIE-ISOLDE facility for this measurement is the possibility to bunch the beam in order to implant a large number of ^{11}Be ions within a short time and subsequently wait for their decay while no beam enters the detector.

Table 1: Decay properties of ^{11}Be. Upper part: Q-value for β decay, half-life and α and proton delayed emission probabilities. Lower part: Q-values for the opened β-delayed particle channels in the decay of ^{11}Be and respective separation energies in the daughter nucleus ^{11}B.

Q_β [keV]	$T_{1/2}$ [s]	$b_{\beta\alpha}$	$b_{\beta p}$
11509.3(5)	13.81(8)	3.47(12)% [a]	$8.3(9)\cdot10^{-6}$ [b]

x	p	n	α	t
S_x(^{11}B) [keV]	11228.6(4)	11454.12(16)	8664.1(4)	11223.6(4)
$Q_{\beta x}$ [keV] [c]	280.7(3)	55.2(5)	2845.1(2)	285.7(2)

[a] Ref. [6]; [b] Ref. [3]; [c] Ref. [7].

The OTPC detector is a standard time projection chamber combined with optical readout of the signals by means of a CCD camera and a photomultiplier tube (PMT). Charged particles transversing the active volume will ionize the gas. Ionization electrons drift in the uniform electric field applied to the active volume and reach the charge-amplification stage at the anode, where light emission occurs. In Figure 2 a schematic representation of the working princicple of the OTPC is given. If all charged particles emitted in the decay are stopped within the active volume of the chamber, the combined information of the CCD image and PMT signal allows to reconstruct the track trajectories in three dimensions [8]. The OTPC operates at atmospheric pressure.

An important feature of the OTPC is the possibility to reduce its sensitivity by means of a gating electrode, when a large charge is expected to be deposited [8]. In this way the amplification stage can be protected from an excess of charge. This characteristic is extremely important when the bunch of ions is deposited into the detector and a large charge is generated. The detector can be switched to high sensitivity within 100 μs after the bunch of ions is implanted, and therefore record their decay.

Since protons in the β decay of ^{11}Be are emitted with low energy, their trajectories will be short. Hence a low-density gas will be used to maximise the track length, namely pure He ($\geq$98%) with a small admixture of N_2 ($\leq$2%) to enhance light emission. It has been shown that deuterons with energies down to 100 keV could be observed (track length $\sim$8$-$10 mm) and their energy measured using the same OTPC and gas mixture [9]. Protons with energies of about 150-200 keV are expected to be observed in this experiment. The βp from ^{11}Be will therefore be clearly detected and their energy measured. In Figure 3 the CCD image and PMT of βd from ^{6}He is shown [9].

It is important to notice that electrons emitted in the β decay are not detected by the OTPC. On the other hand, $\beta\alpha$ emission from ^{11}Be has a probability about four orders of magnitude larger than the decay probability by βp. In oder to avoid overloading the CCD camera image with a background of α particles, the camera will be run in the so-called *movie mode*. The exposition time will be subdivided in several consecutive frames, so that the number of α particles per image is one, maximum two. The oscilloscope will record the PMT signal for the entire exposition duration. A similar mode was successfully used in the measurement of the decay of ^{31}Ar [10]. Each *movie* will be maximum 5 s long. In this

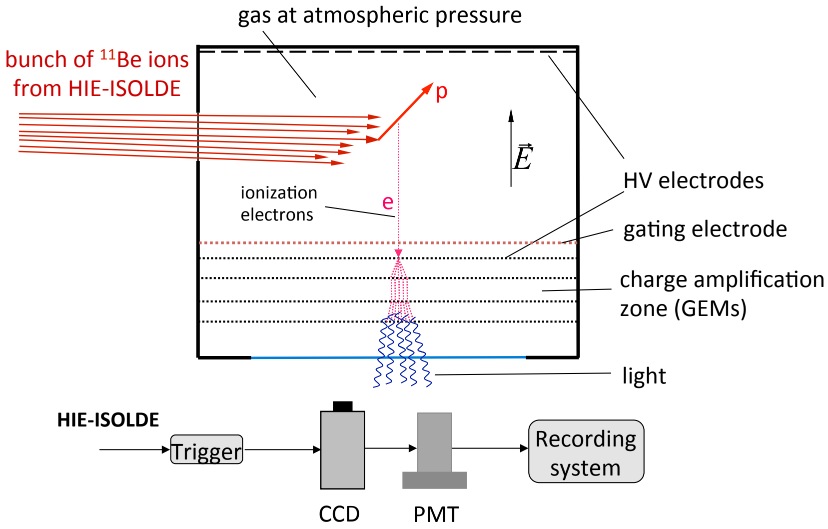

Figure 2: Schematic representation of the OTPC working principle. For each event the data consists of a series of 2D images of given exposure time (*movie mode*) and the total light intensity detected by a PMT as a function of time, recorded by means of a digital oscilloscope.

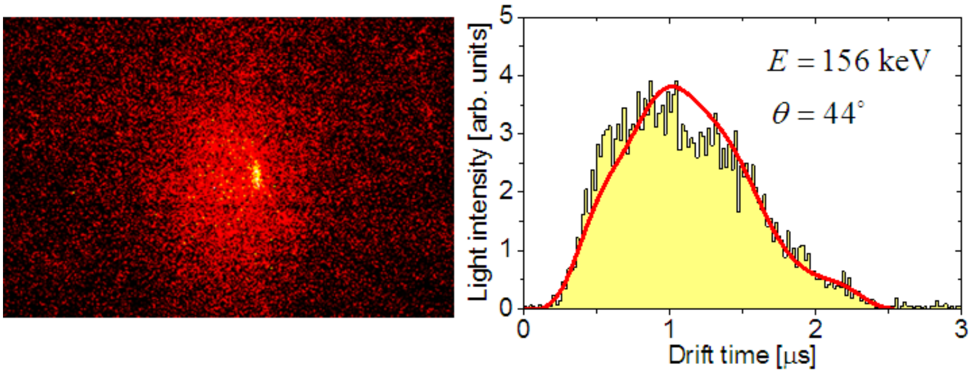

Figure 3: Example of ^{6}He decay into (α+d) for the E$_{\alpha d}$ energy of 156 keV [9]. The CCD image is presented on the left, while the corresponding PMT waveform is shown on the right as a yellow histogram together with the best-fitted SRIM simulation represented by the solid (red) line. The angle θ of the deuteron emission with respect to the horizontal plane is indicated.

way the diffusion of the imlpanted ions in the detector gas will not constitute a problem. The OTPC will be mounted at the end of the HIE-ISOLDE second beamline, just after a vacuum window that separates the accelerator vacuum from air. The bunches of ^{11}Be ions will be accelerated to 7.0 A·MeV and stopped in the center of the detector. Background ions of ^{22}Ne in the postaccelerated beam will not interfere with the measurement, since they will be stopped before reaching the detector.

3 Beamtime estimate and request

The ^{11}Be yield reported in September 2010 in a measurement with Miniball coupled to REX-ISOLDE was of a few 10^5 ions/s with a proton beam of 1.9 μA, UC$_x$ target, RILIS ion source and GPS separator[11]. In the present measurement a yield of about 10^4 ^{11}Be ions/s will be sufficient. This beam intensity will allow to constrain the number of $\beta\alpha$ particles per CCD image to a few and at the same time to gather enough statistics. Assuming the experimental βp branching ratio of $(8.3\pm0.9)\cdot10^{-6}$, a measuring time of 5 s after each bunch and a rate of 1 bunch/30 s, 0.02 protons/bunch will be collected, i.e. 50 protons/day. In order to gather a total of $\sim$300 βp, 6 days of beamtime will be necessary. This will allow not only to confirm the branching ratio value by normalising the number of βp to the number of $\beta\alpha$, but also to measure the energy spectrum of the delayed protons.

Summary of requested shifts: 6 days (18 shifts) of ^{11}Be beam at 7.0 A·MeV at the second beamline and one day (3 shifts) for beam tuning.

References

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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
HIE-ISOLDE 2^{nd} beamline	☒ 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
OTPC	☒ Existing	☒ To be used without any modification (Existing equipment at the University of Warsaw. It will be transported to ISOLDE for the experiment) ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing

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: the OTPC detector functions at about 5 kV DC.

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