EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
Proposal to the ISOLDE and Neutron Time-of-Flight Committee

$d(^{11}\mathrm{Be}, t)$ studied with a new solenoidal spectrometer

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M. Alcorta[1], A. N. Andreyev[2], P. A. Butler[3], J. Cederkäll[4], T. E. Cocolios[5], F. Flavigny[6], B. Fulton[2], H. O. U. Fynbo[7], L. Gaffney[3], R. Gernhäuser[8], D. G. Jenkins[2], D. Joss[3], B. P. Kay[2], O. S. Kirsebom[9], S. Klupp[8], M. Labiche[10], A. Moro[11], A. Murphy[12], D. Mücher[8], G. O'Neill[3], K. Nowak[8], R. Orlandi[6], R. D. Page[3], R. Raabe[6] and A. H. Wuosmaa[13], on behalf of the solenoidal spectrometer collaboration.

[1]*Argonne National Laboratory, USA*
[2]*Department of Physics, The University of York, UK*
[3]*Department of Physics, University of Liverpool, UK*
[4]*Department of Physics, Lund University, Sweden*
[5]*School of Physics and Astronomy, University of Manchester, UK*
[6]*Instituut voor Kern- en Stralingsfysica, KU Leuven, Belgium*
[7]*Department of Physics and Astronomy, Aarhus University, Denmark*
[8]*Physik-Department E12, Technische Universität München, Germany*
[9]*TRIUMF, Canada*
[10]*STFC Daresbury Laboratory, UK*
[11]*Departamento de FAMN, Universidad de Sevilla, Spain*
[12]*School of Physics and Astronomy, The University of Edinburgh, UK*
[13]*Department of Physics, Western Michigan University, USA*

Spokespersons: Oliver Kirsebom [oliverk@triumf.ca], David Jenkins [david.jenkins@york.ac.uk]
Contact person: Magdalena Kowalska [magdalena.kowalska@cern.ch]

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Abstract: We propose to use a new solenoidal spectrometer, currently under development for HIE-ISOLDE, to study the reaction $d(^{11}\mathrm{Be}, t)$ at a beam energy of 8.0 $A\,\mathrm{MeV}$. The main purpose is to extract information on the properties of the bound and, in particular, the unbound states in $^{10}\mathrm{Be}$. This is a proof-of-principle experiment that serves to demonstrate the feasibility of the new experimental approach and pave the way for further studies of 'exotic' structures in light nuclei with the new solenoidal spectrometer. We will also use the experiment to explore the multi-particle coincidence-measurement capabilities of the solenoidal spectrometer.

Requested shifts: 22 shifts
Installation: 2nd beamline

1 Scientific motivation

The beryllium isotopic chain is particularly rich in clustering phenomena. Some well-known examples are $\alpha + \alpha$ cluster structure in ^{8}Be, $\alpha + \alpha + n$ molecular structure in ^{9}Be and $^{10}\mathrm{Be} + n$ halo structure in ^{11}Be [1]. These 'exotic' structures attract considerable attention because we wish to understand how they arise from basic principles and because of their very great importance for stellar phenomena. With the present proposal we wish to investigate 'exotic' structures in ^{10}Be. While the ground state of ^{10}Be is rather well bound, cluster structures are found in the excited states of this nucleus. As an example, experimental efforts during the past 10–15 years have established the likely existence of a rotational band built on the 0_2^+ state at 6.18 MeV [2]. The moment of inertia deduced from the energy separation of the band members is roughly 2.5 times larger than the moment of inertia of the ^{8,9,10}Be ground-state bands, indicating pronounced cluster structure [3]. Calculations within the framework of Antisymmetrized Molecular Dynamics (AMD) predict a molecular structure with two valence neutrons located between two α-particle cores and exhibiting spatial distributions characteristic of σ molecular orbitals [4]. Recent AMD-type calculations predict states in ^{10}Be with different types of cluster structure depending on the excitation energy [5]. Some appear to have been identified experimentally, but their properties remain to be pinned down. Others, such as the 0_3^+ state predicted in Ref. [5], have yet to be identified.

In the proposed experiment, we will be populating excited states up to 19.3 MeV. Breakup thresholds in ^{10}Be below this energy are listed in Table 1. The triton data will allow

Threshold	E_x (MeV)
$n + {}^{9}\mathrm{Be}$	6.81
$\alpha + {}^{6}\mathrm{He}$	7.41
$2n + {}^{8}\mathrm{Be}$	8.48
$2n + 2\alpha$	8.57
$t + {}^{7}\mathrm{Li}$	17.25

Table 1: Breakup thresholds in ^{10}Be below 19.3 MeV.

us to identify states in ^{10}Be and determine their energies and widths. We will use the angular distributions to determine spins and parities of the populated states and to extract spectroscopic factors, which may be compared with theoretical predictions [6] . Finally, we will explore the feasibility of detecting decay fragments in coincidence with the triton. This could potentially allow us to discriminate between different decay modes such as $\alpha + {}^{6}\mathrm{He}$ and $n + {}^{9}\mathrm{Be}$.

2 Background

During the past decade, neutron-rich Li and Be isotopes have been studied in a number of reaction experiments at REX-ISOLDE with post-accelerated beams of ^{8,9}Li and ^{11,12}Be with energies ranging from approximately 2 to 3 A MeV [7, 8, 9, 10, 11]. In these reactions, states in Li and Be isotopes were populated through inelastic scattering and single-neutron transfer reactions on hydrogen and deuteron targets. The light ejectiles were detected using arrangements of segmented ΔE-E silicon telescopes; in one case [11] MiniBall was used to allow coincident detection of γ rays. Structural information was then extracted by the traditional approach of angular-distribution analysis.

Building on these pioneering experiments, we wish to undertake a new study of the $d(^{11}\mathrm{Be}, t)$ reaction at a beam energy of 8.0 $A\,$MeV, using a new solenoidal spectrometer to detect the reaction products. This reaction was one of the several reactions, induced by a ^{11}Be beam on a deuteron target, first studied by Johansen *et al.* [11] at a beam energy of 2.25 $A\,$MeV. The proposed experiment will improve on the previous experiment of Johansen *et al.* in several ways: Firstly, and most importantly, the new solenoidal spectrometer will provide coverage and particle identification at the forward most c.m. angles[1], which is of great importance for the angular-distribution analysis. This angular range could not be covered in the previous experiments because the light ejectiles were stopped in the ΔE detector, thus preventing particle identification. Secondly, the solenoidal spectrometer will provide improved excitation-energy resolution for the light ejectiles. Thirdly, the higher beam energy will allow population of many unbound states, not only the very lowest-lying ones. The higher beam energy will also facilitate the angular-distribution analysis, because 'simpler' direct-type reactions will be favoured.

3 Technical goals

The proposed experiment represents a significant step in the commissioning of the new solenoidal spectrometer at HIE-ISOLDE. We wish to demonstrate the feasibility of detecting light ejectiles at the forward most c.m. angles *with* particle identification. The $d+{}^{11}$Be reaction at 8.0 $A\,$MeV has many open channels and will produce significant backgrounds of protons, deuterons and α particles at forward angles. Particle identification is therefore required to obtain a clean triton spectrum.

We also wish to demonstrate that we can achieve an excitation-energy resolution of approximately 100 keV, which represents a significant improvement compared to the previous REX-ISOLDE experiments. Another important goal is to test the simulation software that is currently being developed for the solenoidal spectrometer. Finally, we will explore the feasibility of detecting decay fragments in coincidence with the triton. A successful demonstration will pave the way for further studies of multi-particle breakups, which is a powerful experimental probe of cluster structure in nuclei.

4 Beam production

In order to produce the ^{11}Be beam, we propose to use a standard Ta target, which gave a yield of up to 10^7 ions/μC in the previous REX-ISOLDE experiment and resulted in a beam intensity of 5×10^6 ions/s on target [12]. We note that these intensities are consistent with the ones given in the ISOLDE yield database: 3.4×10^6 ions/μC with at Ta target and 7.0×10^6 ions/μC with at UC_x target. We will require the use of the ISOLDE laser ion-source (RILIS). Owing to the relatively long half life of ^{11}Be of 13.8 seconds, decay losses will not be a problem. We propose to accelerate the beam to 8.0 $A\,$MeV, which requires fully stripped ^{11}Be ions ($A/q = 2.75$). If necessary, the experiment can also be

[1] Quoted angles always refer to normal kinematics.

performed at lower energy with $^{11}Be^{3+}$ ions, which are produced with higher efficiency in the REX-EBIS. We expect no carbon and oxygen contaminants from the rest gas in the REX-EBIS because there are no stable isotopes of carbon and oxygen with the same A/q ratio as ^{11}Be. Possible contaminants are ^{11}B from the EBIS cathode and ^{22}Ne from the neon buffer gas used in REX-TRAP. There are several ways to suppress these isotopes. First, a stripper foil could be inserted after the final acceleration phase. In this way, the contaminants, $^{11}B^{4+}$ and $^{22}Ne^{8+}$, would be stripped to higher charged states before the mass separation. Second, the REX-TRAP buffer gas could be changed to argon or purified ^{20}Ne, and the boron cathode in EBIS could be replaced with an iridium cathode. In the previous REX-ISOLDE experiment the level of contamination from ^{22}Ne was only 1% using purified ^{20}Ne as buffer gas. No contamination was seen from ^{11}B [12].

5 The new solenoidal spectrometer

The combination of strong kinematic focusing due to inverse kinematics and limited angular resolution results in poor excitation-energy resolution for detection systems based on segmented silicon detectors. As an example, the excitation-energy resolution obtained in the previous REX-ISOLDE experiment was 500 keV (FWHM) [11].[2] In addition, particle identification via the ΔE-E method becomes problematic at the forward most c.m. angles, which are the most important angles for angular-distribution analysis, because the lab kinetic energy of the light fragment is minimized at these angles.

To circumvent these problems, a new solenoidal spectrometer is being constructed for HIE-ISOLDE. This device will be a development of the HELIOS spectrometer, which recently became operational at Argonne National Laboratory [13, 14]. Briefly explained, HELIOS consists of a large-bore superconducting solenoid. Beams enter the solenoid along the magnetic axis and strike a target situated on the magnetic axis. Particles emitted at the target are transported in helical orbits back to the axis where they are detected in a silicon array. From the measured quantities, which are the flight time, the displacement along the beam axis and the energy, the following quantities are derived: mass-to-charge ratio, c.m. energy and c.m. angle. The use of flight times for particle identification requires a bunch separation that is longer than the typical flight time. To this end a prebuncher is being developed for HIE-ISOLDE so that the beam will be bunched to 100 ns.

The first experiments with HELIOS achieved excitation-energy resolutions of approximately 80 keV [14] and 100 keV [15]. It should be noted that the superior energy resolution of HELIOS will be compromised if thick targets are used. For the proposed experiment, we will be using a relatively thin 0.1 mg/cm^2 CD_2 target. Some conventional approaches use γ-ray measurements to recover the excitation-energy resolution. This necessarily introduces an additional efficiency factor of up to 10% due to the coincidence requirement. A solenoidal system allows good resolution, sufficient for many purposes, from the measurement of outgoing ions alone and thus avoids the reduction in efficiency.

[2] Note that this experiment made use of a rather thick 1 mg/cm^2 CD_2 target; target loss effects were an equally great source of resolution loss for this experiment.

6 Kinematics and simulations

Kinematic curves of the $d(^{11}\mathrm{Be}, t)$ reaction at 8.0 A MeV for three representative excitation energies in ^{10}Be (E_x) are shown in Fig. 1. The tritons are seen to be limited to the forward hemisphere. The low-energy tritons correspond to forward c.m. angles and are the most interesting ones from the point of view of the angular-distribution analysis. Tritons below a few hundred keV will be difficult to detect due to electronic noise. This could potentially complicate the study of the lowest-lying bound states ($E_x < 2$ MeV), but will not affect the analysis of the higher-lying states that are our primary interest. The silicon detectors will be 700 μm thick, enough to stop 15 MeV tritons. Preliminary simulations have been

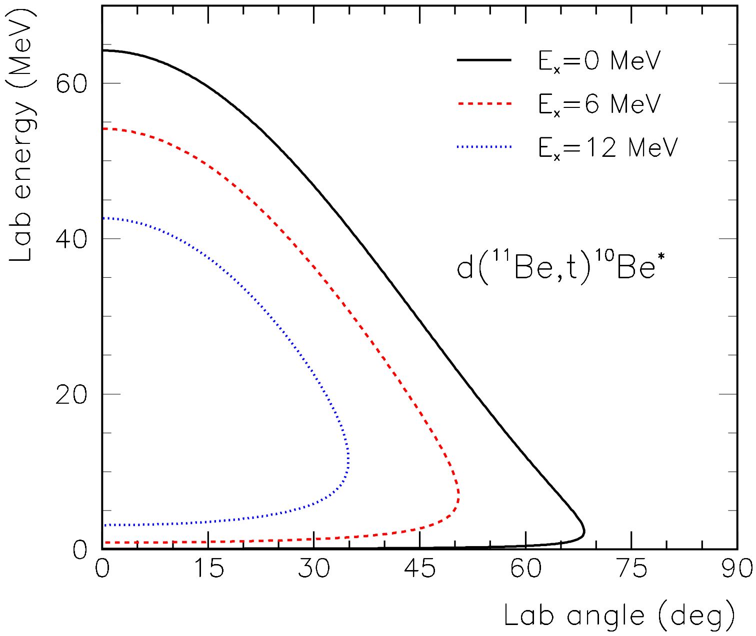

Figure 1: Kinematic curves of the $d(^{11}\mathrm{Be}, t)$ reaction at 8.0 A MeV for three representative excitation energies in ^{10}Be (E_x).

performed assuming a 3 Tesla magnetic field and a 70 cm long silicon array, placed 20 cm downstream of the target. The simulations show that we will be able to cover excitation energies up to roughly E_x = 12 MeV and a relatively wide range of c.m. angles, e.g. 0°–40° at E_x = 6 MeV. A stronger magnetic field will allow us to cover higher excitation energies.

7 Beam-time request

From the previous REX-ISOLDE experiment [11] we know that the 2^+ state in ^{10}Be at 7.54 MeV is fairly strongly populated in the $d(^{11}\mathrm{Be}, t)$ reaction. This state is thought to be the second member of the strongly deformed molecular rotational band built on the 0_2^+ state at 6.18 MeV. This, and the controversy regarding its partial α width [2], makes it a very interesting state. For these reasons, we base our request of beam time on an estimate of how many shifts are required to make a precise measurement of its angular distribution.

Based on the data obtained at lower energy in the previous REX-ISOLDE experiment, $d\sigma/d\Omega \approx 10$ mb/sr appears to be a reasonable estimate within a factor of 2 to 3 [11]. Our simulations show that we will cover c.m. angles between 0° and 40°, corresponding to a solid angle of 1.5 sr, and hence $\sigma \approx 15$ mb. We assume the beam intensity obtained in the previous REX-ISOLDE experiment, i.e. 5×10^6 ions/s on target. Finally, we will use a relatively thin 100 μg/cm^2 CD_2 target in order not to compromise the superior excitation-energy resolution of the solenoidal spectrometer. Based on these data, we estimate the event rate to be 2×10^3 hour^{-1}. To collect 10^5 events, which is necessary to have a precise measurement of the angular distribution, we thus require 49 hours, corresponding to 6 shifts. Given the large uncertainties associated with the estimate, we ask for twice as many shifts, i.e. 12 shifts. In addition, we ask for 6 shifts to perform a background measurement on a carbon target and 4 shifts for stable-beam adjustments and calibration. We thus ask for a total of 22 shifts.

8 Summary

We propose a proof-of-principle experiment for the new solenoidal spectrometer, currently under development for HIE-ISOLDE. Taking advantage of the experience gathered in previous studies with post-accelerated Li and Be beams at REX-ISOLDE, we will use the solenoidal spectrometer to study the reaction $d(^{11}\mathrm{Be}, t)$ at a beam energy of 8.0 A MeV. From the triton data we will determine energies and widths of unbound states in ^{10}Be and we will use the angular distributions to determine spins, parities and spectroscopic factors. Additionally, we will attempt to detect charged breakup fragments in coincidence with the triton. It is hoped that these results will shed light on the 'exotic' cluster structures in the excited states of ^{10}Be. The solenoidal spectrometer provides coverage and particle identification at the forward most c.m. angles, which is a significant advantage for the angular-distribution analysis. It also provides superior excitation-energy resolution. We request a total of 22 shifts to perform the experiment.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: *new solenoidal spectrometer*

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

Additional hazards:

Hazards	$d(^{11}\mathrm{Be}, t)$	[Part 2 of experiment/ equipment]	[Part 3 of experiment/ equipment]
Thermodynamic and fluidic			
Pressure			
Vacuum			
Temperature			
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	LHe, 1650 [l] LN_2, 200 [l]		
Electrical and electromagnetic			
Electricity			
Static electricity			
Magnetic field	3 [T]		
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material	CD_2		
Beam particle type (e, p, ions, etc)	^{11}Be		

Beam intensity	5×10^6 s^{-1}		
Beam energy	8.0 MeV/u		
Cooling liquids			
Gases			
Calibration sources:	☒		
• Open source	☐		
• Sealed source	☒		
• 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 (1-300 MHz)			
Chemical			
Toxic	[chem. agent], [quant.]		
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