EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

(Following HIE-ISOLDE Letter of Intent I-108)

Studies of unbound states in isotopes at the $N = 8$ shell closure

June 2, 2015

M.J.G. Borge,[1], L.M. Fraile[2], H.O.U. Fynbo[3], R. Gernhäuser[4], A. Heinz[5], A. Howard[3], J.G. Johansen[3], H.T. Johansson[5], B. Jonson[5], O.S. Kirsebom[3], T. Kröll[6], S. Lindberg[5], D. Mücher[4], T. Nilsson[5], S. Paschalis[6], M. Petri[6], R. Raabe[7], K. Riisager[3], O. Tengblad[8], R. Thies[5], P. Van Duppen[7] and the MINIBALL and T-REX collaborations

[1] *PH Department, CERN, CH-1211 Geneve 23, Switzerland*
[2] *Grupo de Fisica Nucelar, Universidad Complutense, CEI Moncloa, E-28049 Madrid, Spain*
[3] *Department of Physics and Astronomy, Aarhus University, DK-8000 Aarhus C, Denmark*
[4] *Physik-Department E12, Technische Universität München, Garching, Germany*
[5] *Fundamental Fysik, Chalmers Tekniska Högskola, Göteborg, Sweden*
[6] *Institut für Kernphysik, Technische Universität Darmstadt, Darmstadt, Germany*
[7] *Instituut voor Kern- en Stralingsfysica, K.U. Leuven, B-3001 Leuven, Belgium*
[8] *Instituto de Estructura de la Materia, CSIC, E-28006 Madrid, Spain*

Spokesperson: J.G. Johansen (jgj@phys.au.dk)
Contact person: M. Madurga (madurga@cern.ch)

Abstract: We propose to study low-lying resonances in the two unbound isotopes ^{13}Be and ^{10}Li as well as low-lying resonances in ^{12}Be. This will be done using an ^{11}Be beam impinging on a tritium target leading to one or two particle transfer reactions. The decay scheme of the resonances will be studied using the MINIBALL and differential cross sections will be determined using T-REX.

Requested shifts: 21 shifts, (split into 1 run over 1 year)
Installation: MINIBALL + T-REX

1 Introduction

This proposal is based on the Letter of Intent INTC-I-108. The aim of the experiment is to study ^{13}Be for the first time in a low-energy transfer experiment. We will be using an ^{11}Be beam incident on a tritium target to produce ^{13}Be via a 2n-transfer. The T-REX setup will be used to detect protons, and light charged particles from other reactions, which can be used to determine the resonance energies and differential cross sections for the lowest lying levels. The MINIBALL will enable us to study gamma-decays from excited states in ^{12}Be, including the long-lived 0_2^+-state, after the neutron decay. Beside the (t,p)-channel other interesting channels are open. Of special interest is (t,α) and (t,d), which allows us to study ^{10}Li and ^{12}Be respectively as well. Transfer reactions using the ^{11}Be-beam and a deuteron target at ISOLDE have already been performed with great success [1]. The same goes for reaction with the tritium-target, which was initially used in a study of ^{32}Mg [2] and later in several other experiments at MINIBALL and T-REX.

2 Physics cases

^{13}Be

The focus of this experiment is the study of ^{13}Be. ^{13}Be is a neutron unbound nucleus and the first unbound isotope among the $N = 9$ isotones. Systematical studies of the $N = 7$ and $N = 8$ isotone chains have shown a clear lowering of the $\nu 2s_{1/2}$ and $\nu 1d_{5/2}$ single-particle orbits with respect to the $\nu 1p_{1/2}$, which leads to the inversion of the $1/2^-$ and $1/2^+$-states in ^{11}Be and the breaking of the $N = 8$ magic number in ^{12}Be. Indications of a similar lowering of especially the $\nu 2s_{1/2}$ orbit have been seen in ground state studies of ^{15}C and ^{14}B.

Furthermore, ^{13}Be plays an important role in the understanding of the structure of ^{14}Be. ^{14}Be is a Borromean two-neutron halo nucleus, and the ^{12}Be+n interaction is an important part of the 3-body calculations performed for this isotope. A good knowledge of ^{13}Be is required to theoretically describe ^{14}Be. A present the experimental data, like binding energy and radius, for ^{14}Be cannot be reproduced using the existing knowledge on the ^{13}Be energy levels [4, 5].

^{13}Be has been studied in several experiments over the last decades, see [3] and references therein. This includes a ^{12}Be(d,p) transfer experiment using a 55 AMeV ^{12}Be beam [6]. The level structure of ^{13}Be is still not well established despite these efforts. The strucure of the low-energy levels in ^{13}Be has been discussed in two recent papers [3, 7] based mainly on three recent knock-out experiments performed at RIKEN, GSI and GANIL [9, 3, 7]. The existence of two low-energy levels has been established. Those are a narrow $1/2^+$ resonance around 0.5 MeV (E_r) above the neutron threshold, and a $5/2^+$ resonance with an energy around $E_r = 2 - 2.5$ MeV. The width of the latter is still not clear with experiments suggesting $\Gamma \approx 0.5$ MeV and $\Gamma \approx 1.5$ MeV. Indications for several other levels have been seen, the most prominent ones have energies (above the neutron threshold) of $E_r = 0.8$ MeV (suggested spins and parities are $1/2^-$ or $5/2^+$), $E_r = 3.0$ MeV ($1/2^+$ or $1/2^-$) and $E_r = 5.2$ MeV ($5/2^+$). An overview of the suggested level structures in ^{13}Be is shown in Fig. 1.

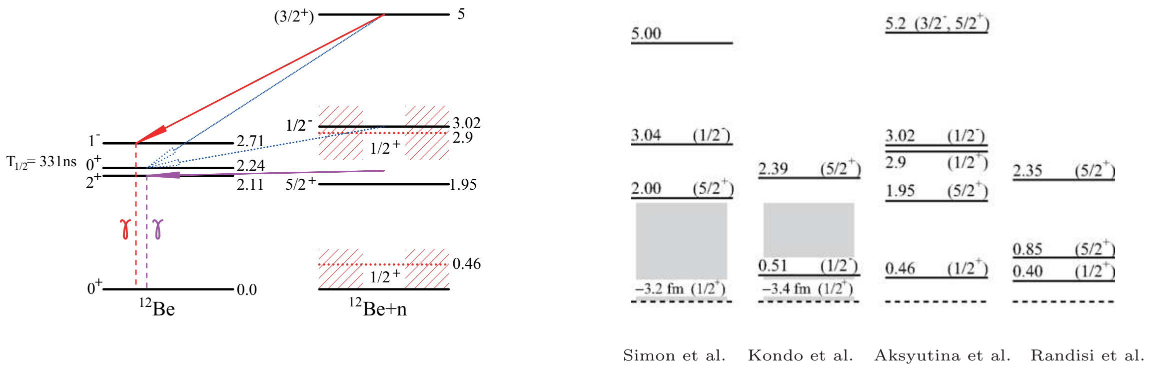

Figure 1: An overview of the current knowledge on ^{13}Be. Left: The level structure taken from [3] including the decay scheme. Right: The level structure of ^{13}Be extracted in four different knock-out reaction experiments. The illustration is taken from [7] and the level structures are taken from [8, 9, 3, 7]

The energy spectra calculated for the three knock-out experiments were based on invariant-mass calculations using the energy of the emitted neutron and ^{12}Be. This method requires knowledge of the excitation energy of the daughter nucleus, since excitation energy shifts the energy determined by the invariant mass. Detection of gamma decays is therefore required to properly identify the resonance energies in ^{13}Be. Gamma decays were measured in the experiment at RIKEN, but only from decays of the 2_1^+- and the 1_1^--states in ^{12}Be. The first one was populated from the $5/2^+$ resonance at $E_r = 2$ MeV and the latter by the resonance at $E_r = 5.2$ MeV. A third excited state is present in ^{12}Be, a long lived ($\tau = 330$ ns) 0_2^+-state at $E^* = 2.2$ MeV. None of the experiments were able to detect this state, due to its long lifetime, but it is likely to be populated in decays from states above 2 MeV.

Our proposed experiment will provide a complimentary way to study these low-energy levels in ^{13}Be including their decays to ^{12}Be. This experiment will probe ^{13}Be from the low-mass side rather than the high mass, which will enable us to probe other single-particle structures in ^{13}Be. The suggestion of a $1/2^+$ ground state and a $1/2^-$ slightly above, see Fig. 1, is strikingly similar to the situation in ^{11}Be. The 2n-transfer reaction is expected to proceed via a one- or a two-step process, with the one-step being the dominating one. In the one step process the two neutrons will be transfered together, which will lead to a population of $1/2^+$-states, since the ground state of ^{11}Be is a $1/2^+$-state as well. There are two types of two-step processes to consider, either a sequential transfer of the two neutrons, or the excitation of the ^{11}Be nucleus along with the 2n-transfer. The prior is expected to lead to the population of $1/2^+$, $1/2^-$ and $5/2^+$ states, while the latter should populate a $1/2^-$ state, if present.

We determine the resonance energies using the energy and momentum of the proton, a method independent of the decay of ^{13}Be. This experiment will therefore provide a cleaner excitation energy spectrum and we do not rely on the detection of the decay from the isomeric 0_2^+-state in ^{12}Be. The expected resolution of the determined excitation energy will be 300 keV (σ) based on experience from previous experiments at ISOLDE. This should be sufficient to separate the 2 MeV, 3 MeV and 5.2 MeV resonances depending

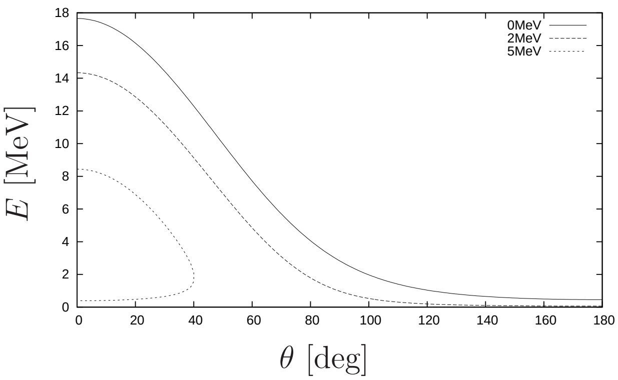

Figure 2: Energy vs. laboratory angle for emitted protons at three different excitation energies: 0 MeV, 2 MeV and 5 MeV.

on their width, but not sufficient to separate the 0.5 MeV from the proposed 0.8 MeV resonance.

The Q-value of the reaction is Q = -5821.1 MeV, hence we will be able to populate all the states up to the 5.2 MeV with a beam energy of 5 MeV/u. Fig. 2 shows the energy as a function of the laboratory angle for the outgoing proton in reactions at three different energies in ^{13}Be. It is clear from this figure, that we will be able to detect reactions populating all these states, but the angular range, both in laboratory and center of mass, will be very limited as soon as we go above 2 MeV excitation energy. We will therefore only aim at measuring differential cross sections for the lowest resonances. Additionally we will focus on studying the width of the resonances and the decay scheme of ^{13}Be. The width of most of the resonances is not well determined and some of them vary significantly between the different experiments. The decay scheme plays an important role in the analysis of the knock-out experiments as mentioned before and will provide further insight into the structure of the nucleus. We will use the MINIBALL to detect gamma decays in ^{12}Be. All known gamma lines in ^{12}Be, including decays from the long-lived isomeric 0_2^+-state, have already been detected using the MINIBALL [1].

Other reactions

Other channels will be open in this experiment. Of special interest are the channels ^{11}Be(t,α)^{10}Li (Q = -350.6 keV) and the ^{11}Be(t,d)^{12}Be (Q = -3088 keV). ^{10}Li is, like ^{13}Be, a neutron-unbound nucleus which plays an important role in the understanding of a Borromean nucleus [10]. The level structure of ^{10}Li is better understood than the one in ^{13}Be, but we believe this method will provide additional experimental information on ^{10}Li. This channel will also be used to test T-REX's ability to do particle coincidence measurements. A large background of α-particles is expected in the experiment, but the low mass of ^{10}Li leads to a large outgoing angle of the nucleus. The maximum outgoing angle of ^{9}Li after emission breakup is 18°, which is sufficient to detect the nucleus in the forward CD detector of T-REX. The particle coincidence measurement should be possible even at an excitation energy of $E^{*} = 5$ MeV. The coincidence measurement will provide an additional gate that can be used to reduce the α-background. Additionaly the coincident detection will enable a reconstruction of the neutron emission energy, which

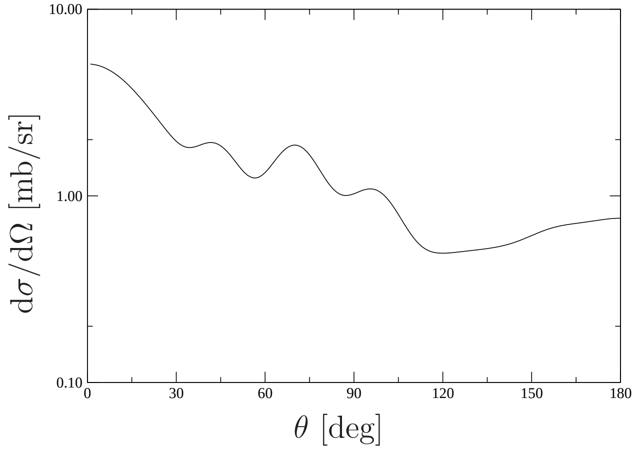

Figure 3: A DWBA calculation of the ^{11}Be(t,p)^{13}Be populating the $1/2^+$ resonance at $E_r = 0.5$ MeV in ^{13}Be. The calculations are based on potentials taken from [15].

will improve the determination of the excitation energies.
The ^{11}Be(t,d) reaction will allow us to study ^{12}Be. ^{12}Be has been studied previously in several nucleon transfer experiments including one at ISOLDE. The bound states in ^{12}Be are well understood, but lately the attention has moved toward low-lying resonances. The lowest-lying resonance known in ^{12}Be has an excitation energy of $E^* = 4.5$ MeV. This resonance has been seen in several experiments [11, 12], but the quantum numbers are not yet known, and theoretical models predict spins between 0 and 3 and both, negative and positive parity [13, 14]. Our aim is to provide additional experimental information to this discussion by measuring this state and by determining the branching ratio of the decay.

3 Setup and beam requirements

We will be using the MINIBALL setup with the T-REX silicon array. T-REX consists of eight PSD's in a square barrel covering angles from 30-80° and 105-150°. In addition we will have a CD detector covering the very forward laboratory angles (7-25°). The forward CD is crucial to detect particles from the highest-lying resonances as well as for detecting fragments in coincidence with the light particles, like ^{9}Li in the ^{11}Be(t,α)^{10}Li. An additional hpGe detector will be placed at the beam dump to detect gammas from the long lived 0_2^+-state in ^{12}Be.
The main target is a tritium-loaded titanium foil with a thickness 40 μg/cm^2. Three additional targets will be used as well: a pure titanium foil, a silver foil and a thick aluminum foil. The tritium target has been used for transfer reactions at REX-ISOLDE before (IS470, IS499, IS504) and follows CERN specification No 4229RP20070405-GD-001.
We plan to run on fully ionized Be with an $A/q = 11/4$ and a beam energy of 5 MeV/u. The main contaminant is ^{22}Ne, which can be accelerated on $A/q = 11/4$ as well. We require therefore purified ^{20}Ne as buffer gas in the EBIS. The beam intensity in the previous ^{11}Be run at REX-ISOLDE was $5 \cdot 10^6$ s^{-1} and we expect a similar or slightly

higher beam intensity with HIE-ISOLDE. DWBA calculations have been made and the estimated cross section for the population of the ground state resonance is shown in Fig. 3. The calculated cross section should only be used to estimate the count rate. A much more detailed calculation is needed to describe the reaction process. The calculation of transfer reactions to the continuum is currently a very active area, with a lot of ongoing development [16], and we are collaborating with one of the leading persons, A. Moro. The calculation gives an estimate of 1 mb/sr, which will lead to a proton detection rate of 0.1 /s or about 3000 protons per shift. The MINIBALL has a 4% detection efficiency at 2 MeV, which will lead to 120 proton-gamma coincidences per shift.
We request 15 shifts with ^{11}Be on the primary target, 4 shifts for background measurements (two shifts on the pure titanium foil and two shifts with the neon buffer gas) and 2 shifts for beam intensity measurements and energy and efficiency calibration with ^{11}Be, in total 21 shifts.
Summary of requested shifts: 21 shifts in one run. MINIBALL+T-REX installation.

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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
MINIBALL + T-REX	☒ Existing	☒ To be used without any modification

HAZARDS GENERATED BY THE EXPERIMENT

Hazards named in the document relevant for the fixed 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	^{3}H (as in IS470, IS499, IS504) less than 10 GBq		
Beam particle type	^{11}Be		
Beam intensity	$6 \cdot 10^6$		
Beam energy	5 MeV/u		
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	ISOLDE triple alpha source		
• Open source	■		

• Sealed source	☐	■	
• Isotope		152Eu	
• 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