CERN-INTC-2004-023
INTC-P-187
13 October 2004.

Proposal to the ISOLDE & NTOF Committee

Study of neutron-rich Be isotopes with REX-ISOLDE

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Abstract

We propose to perform a survey experiment with a ^{11}Be beam reacting with a deuteron target at REX-ISOLDE at a beam energy of 3.1 MeV/u. The purpose of the experiment is to extract information on ^{10,11,12}Be and ^{9}Li via different nuclear reactions. Furthermore we suggest to explore the possibility to produce a ^{12}Be beam.

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1 Introduction and motivation

The REX-ISOLDE postaccelerator has recently delivered its first physics results. Among them are our transfer reaction studies with ^{9}Li on a deuteron target where results were obtained for ^{8}Li and ^{10}Li (IS367, [1, 2]). In this our first REX-ISOLDE experiment several states were seen and could be separated in ^{8}Li, and a structure at 300 keV excitation energy was seen in ^{10}Li, which might contain contributions from several states. We propose to continue our reaction studies with ^{11,12}Be beams, the motivation being to derive in a similar way structural information on the Be-isotope series. There are two distinct aspects to this motivation: The first is that we can exploit the fact that much is known on ^{11}Be and the neighbouring isotopes from reaction experiments at higher energies, due to this (and to its simple structure) it is therefore a perfect case for comparing structure studies at low and higher energies. (The recently discovered discrepancy between B(E2) values for ^{32}Mg extracted from high- and low-energy experiments shows the need for such a comparison.) This holds in particular for the ^{11}Be(d,t)^{10}Be transfer reaction. The second is that we expect to be able to derive new structure information in particular for the ^{11}Be(d,p)^{12}Be transfer, as we shall argue below. Reaction studies with a ^{12}Be beam could reach the unbound ^{13}Be nucleus and be very interesting. Our first goal in this direction is to establish a beam at REX-ISOLDE of this short-lived (23.6 ms) isotope, which is produced with high yield at ISOLDE.

We mention in passing that this investigation will complement the earlier beta-decay studies of Be-isotopes done at ISOLDE by some of us (IS374), where new information was obtained on ^{12}Be and ^{14}Be [3, 4].

The neutron-rich Be-isotopes have in recent years been a laboratory for several topical phenomena:

(i) halo states. The nucleus ^{11}Be is the generic example of a one-neutron halo and its structure is quite well known by now after a decade of reaction studies at beam energies from 20 MeV/u and upwards. Examples are the early break-up studies at GANIL [5] and RIKEN [6], the knockout reactions to states in ^{10}Be and ^{10}Li performed at MSU [7, 8], the ^{11}Be(p,d)^{10}Be transfer reaction at 35 MeV/u at GANIL [9] and the break-up measurement at 250 MeV/u at GSI [10]. Not to be forgotten is the magnetic moment measurement at ISOLDE [13]. Many theoretical analyses have also been performed, two recent examples are coupled discretized continuum channels descriptions of the one-neutron removal [11] and elastic and inelastic scattering [12]. Aiming initially only at the structure of ^{11}Be, the interplay with the structure of the surrounding nuclei have now come more into focus.

(ii) vanishing of magic numbers. In ^{11}Be the breaking of the N=8 magic number causes the famous inversion such that the ground state is $1/2^{+}$ and the first excited state $1/2^{-}$. Both of these states are one-neutron halo states. That a similar breaking takes place in ^{12}Be has been argued for a long time based on the beta-decay halflife [14], this has been confirmed through analysis of the one-neutron knockout from ^{12}Be to ^{11}Be ground state and 1st excited state [15]. This implies that the structure of the ground state of ^{12}Be is similar to that of ^{11}Li with p-shell and sd-shell admixture of the last two neutrons. Note that the breaking of N=8 is the only case where ab-initio variational and Greens-functions Monte-Carlo calculations can be performed.

(iii) molecular states. The Be isotopic chain has also played a central role for the topic of molecular states in nuclei consisting of α-particle cores with neutrons in molecular-like orbits. In ^{12}Be such states have been seen experimentally at 10-25 MeV excitation energy from inelastic scattering of ^{12}Be off a $(CH_2)_n$ target [19, 20]. Excited states in ^{10}Be have also been interpreted within this framework. See e.g. [21] and references therein for

information on the theoretical modelling of these structures.

The proposed reaction with a ^{11}Be beam will be the first transfer reaction experiment with a halo nucleus at REX-ISOLDE. The low breakup energy of the projectile will influence the course of the reaction, as already seen at higher beam energies, and both break-up of ^{11}Be and inelastic scattering to the sole bound level at 320 keV will present an experimental challenge. There will be many open reaction channels as also seen for the case of ^{9}Li, so we expect that a two-stage approach will be most fruitful with a first run aimed at obtaining an overview of the different reaction channels followed by a more dedicated study in a second run.

There are two advantages when using a ^{11}Be beam. The first is its rather favourable beta-decay properties with a halflife of 13.8 s, which implies that decay losses will not be a problem, and only a 2.9% branch of delayed particles.

The second is that no carbon and oxygen contamination from the rest-gas in the EBIS will be present (as seen in the ^{9}Li case [1, 2]). There might still be contaminations; ^{11}B from the EBIS cathode and ^{22}Ne used as buffer gas in REX-TRAP. If these contaminations should turn out to be a problem there are several approches to minimize this. Firstly, if fully charged ^{11}Be would be accelerated a stripping foil after the REX-LINAC could remove most of the ^{11}B^{4+} and ^{22}Ne^{8+} which would be stripped to higher charge states before being mass separated. Secondly, the buffer gas in REX-TRAP could be changed to ^{40}Ar, and the ^{11}B cathode could be exchanged with an irridium cathode.

2 Excited states in ^{12}Be

Although the excited states of ^{12}Be are not that well studied, interesting information has appeared during the last decade. In Table 1 we have collected the presently available experimental knowledge. On the theoretical side many different models have been applied, including the shell-model [14, 22, 23], three-body models based on a core plus two neutron structure [24, 25, 26] and the antisymmetrized molecular dynamics model [21] (only the most recent papers are cited).

The models differ somewhat in the predicted spectra, but agree that one consequence of the breaking of the N=8 magic number is the appearence of a low lying 0^+ state, experimentally found as an isomer [18] at 2.24 MeV. Many, but not all, models also predict a 1^- state below the neutron threshold at 3.17 MeV, the state seen earlier at 2.730 MeV is now known [17] to have these quantum numbers. The remaining particle bound state is a 2^+ state at 2.111 MeV. An interesting observation was made in [26], namely that the three-body models that place the two outer neutrons in $s^{1/2}$ and $p^{1/2}$ orbits naturally predict a spectrum with excited 0^+, 1^- and 2^+ states. Since all these states experimentally are less than about 1 MeV from the one-neutron threshold (the two-neutron threshold is only 0.5 MeV higher), one would therefore expect binding energy effects to be important for their structure. On the other hand other models include contributions from the $d_{5/2}$ orbit or excited core contributions [25], so the question whether the excited states do have halo structure must be answered experimentally.

Some electromagnetic transition rates are already known. Our proposed experiment will add more information through the ^{11}Be(d,p)^{12}Be reaction. Shell-model calculations [23] predict spectroscopic factors of 1.16, 0.04, 0.41 and 0.68 for transitions to the 0_1^+, 0_2^+, 2^+ and 1^- states. In contrast some three-body models seem to favour a $(p_{1/2})^2$ configuration for the 2^+ state which would give a very small transfer probability. We note that the interpretation of the data must include consideration both of the (orbital) configuration of the levels and of the possible halo structure, none of the present models provide this.

State	Energy (MeV)	J^π	Width/lifetime	Reference
gs	0.0	0^+		[16]
1st	2.111±0.003	2^+		[16]
2nd	2.24±0.02	0^+	Isomer, 50 ns $< \tau <$11 μs	[18]
3rd	2.730±0.003	(0^+)		[16]
	2.68±0.03	1^-		[17]
4th	4.580±0.005	(2^+)	Γ=107±17 keV	[16]
5th	5.724±0.006	$(2^+,3^-,4^+)$	Γ=86±15 keV	[16]

Table 1: Energy levels of ^{12}Be, the 1n threshold is positioned at 3.17 MeV, the 2n threshold at 3.67 MeV.

3 The intended approach at REX-ISOLDE

As mentioned earlier we envisage a two-stage approach starting with a survey based exclusively on particle detection. In this first step cross sections for the individual channels will be extracted and the cases where gamma-detection are needed to cleanly separate excited states in the final nuclei will be identified. Through theoretical analysis we should also establish the relative importance of direct and compound reactions and hopefully extract optical potentials and some first spectroscopic factors. This will form the basis for the second stage with more detailed measurements. We comment in the following briefly on the individual reaction channels.

3.1 ^{11}Be beam

^{11}Be elastic scattering on a deuteron target. The main problem in this channel is to separate the elastic scattering from the inelastic scattering to the 320 keV excited state. This would require a good spatial and energy resolution for the detected particles as seen in figure 1. The possible break-up reaction ^{11}Be(d,dn)^{10}Be will also be measured in this channel (the break-up threshold is shown as a dashed line in figure 1).

^{11}Be(d,t)^{10}Be. The neutron transfer reaction onto the target could be expected to have a large cross section. It can be directly compared to the ^{11}Be(p,d)^{10}Be reaction measured at 35 MeV/u [9] as well as the knock-out reactions mentioned above, the comparison of spectroscopic factors extracted from high-energy and low-energy experiments might be particularly interesting. As shown in figure 2 we can populate and detect excited states up to about 9 MeV in ^{10}Be (the Q-value of the reaction is 5.75 MeV). This region includes unbound states, the 1n separation energy of ^{10}Be is 6.812 MeV and the breakup threshold for ^{6}He+α 7.413 MeV.

^{11}Be(d,p)^{12}Be. The neutron transfer onto the projectile will feed states in ^{12}Be. The Q-value of this reaction is 0.944 MeV, so we can populate states up to more than 5 MeV, as shown in figure 3. The aim here is to extract spectroscopic factors, which for the ground state can be compared to those extracted from the ^{12}Be one-neutron knock-out reaction [15], while for the excited states nothing is known so far.

^{11}Be(d,alpha)^{9}Li. This reaction can in principle reach all known excited states in

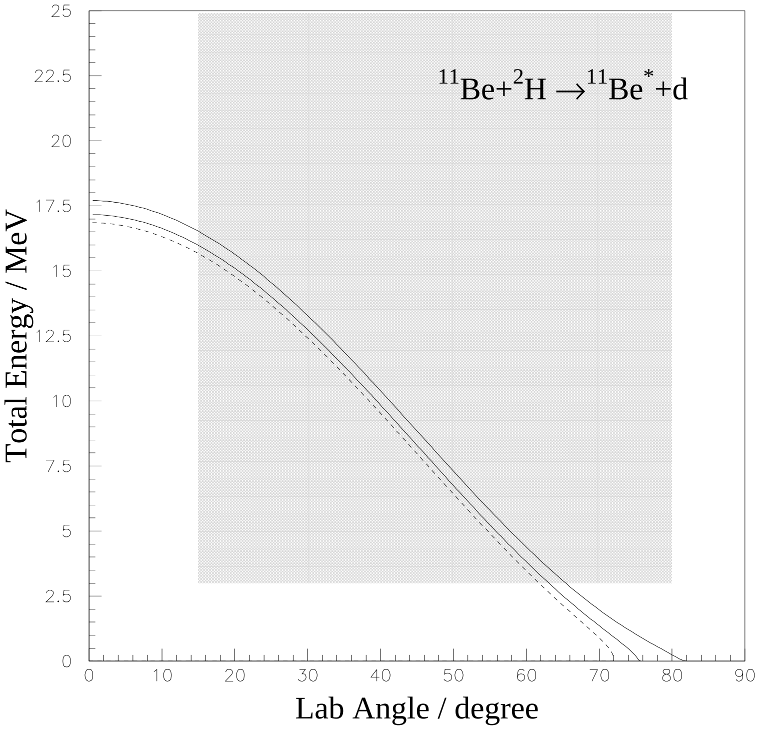

Figure 1: Kinematic curves for the ^{11}Be(d,d)^{11}Be reaction at 3.1 MeV/u going to final states at excitation energy 0 and 0.320 MeV. The dotted line shows the one-neutron separation energy (0.503 MeV). The shaded square shows the region where reaction products can be identified.

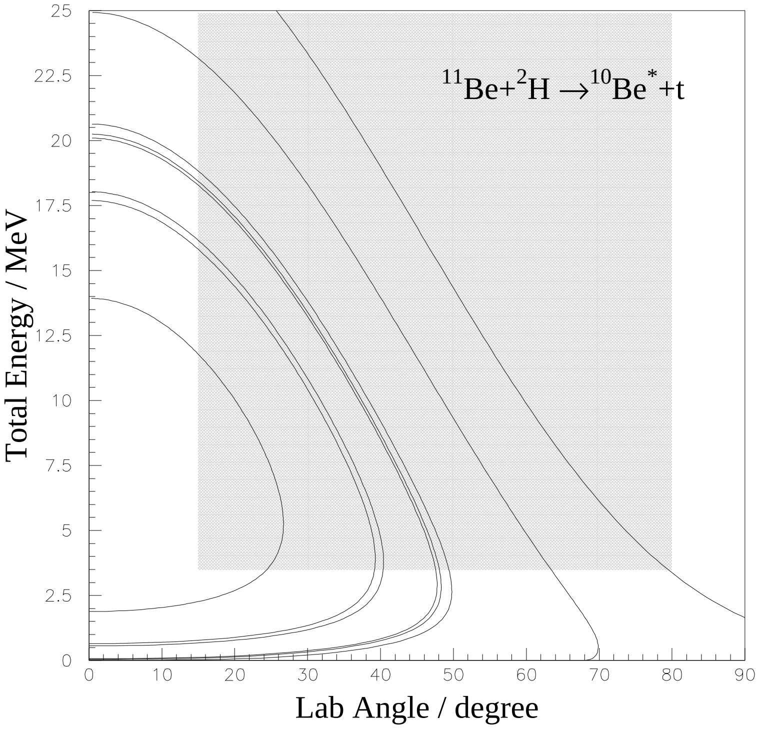

Figure 2: Kinematic curves for the ^{11}Be(d,t)^{10}Be reaction at 3.1 MeV/u going to final states at excitation energy 0, 3.368, 5.960, 6.179, 6.263, 7.371, 7.542 and 9.270 MeV. The shaded square shows the region where reaction products can be identified.

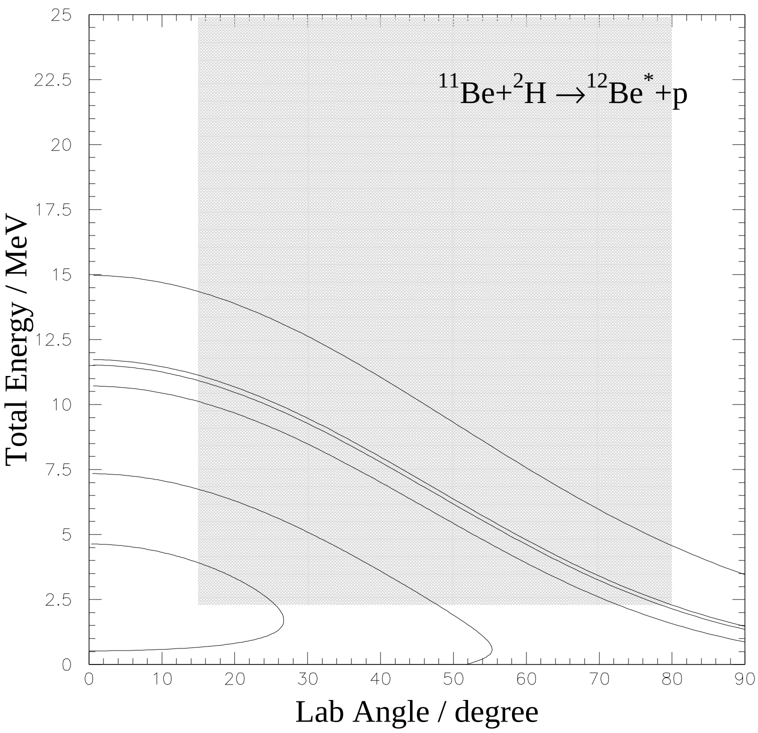

Figure 3: Kinematic curves for the ^{11}Be(d,p)^{12}Be reaction at 3.1 MeV/u going to final states at excitation energy 0, 2.111, 2.240, 2.730, 4.580 and 5.724 MeV. The shaded square shows the region where reaction products can be identified.

^{9}Li, see figure 4 (the Q-value is 5.93 MeV). The 1n separation energy of ^{9}Li is 4.064 MeV, for 2n it is 6.097 MeV. We should also be able to reach the triton threshold at 7.59 MeV, this might be an interesting region to look for states with a t+^{6}He cluster structure.

3.2 ^{12}Be beam

A ^{12}Be beam at REX-ISOLDE would allow studies similar to those mentioned above for a ^{11}Be beam, thereby e.g. giving access to information on the unbound system ^{13}Be. The short half-life of the order 20 ms makes this non-trivial, and the fact that there is a rest gas beam from ^{12}C at all possible charge-states further complicates the ^{12}Be case. In this case an active removal of ^{12}C from the REX-ISOLDE beam is most likely necessary to be able to perform measurements on ^{12}Be. In the case of ions in charge state +4 one possibility would be to insert a carbon-foil after the linac structure in which most of the ^{12}C would be stripped to 6+ ions (less than 1% in 4+) thus reducing the ^{12}C contamination by more than two orders of magnitude and only reducing the ^{12}Be 4+ ions by a few % (see eg. [27] for information on stripping of ions through carbon-foils). This method has already been shown to work at an experiment at REX-ISOLDE in 2004 (IS424).

We therefore suggest to make an exploratory study of the possibility of using ^{12}Be as a beam at REX-ISOLDE.

The proposed way of investigating the ^{12}Be yield and possible contaminations is by applying the method of elastic resonance scattering of protons in a thick target (as applied in IS371 [2]). In this way the expected ^{12}C contamination can easily be monitored via the elastically scattered protons detected at forward angles, while the ^{12}Be yield, all stopped

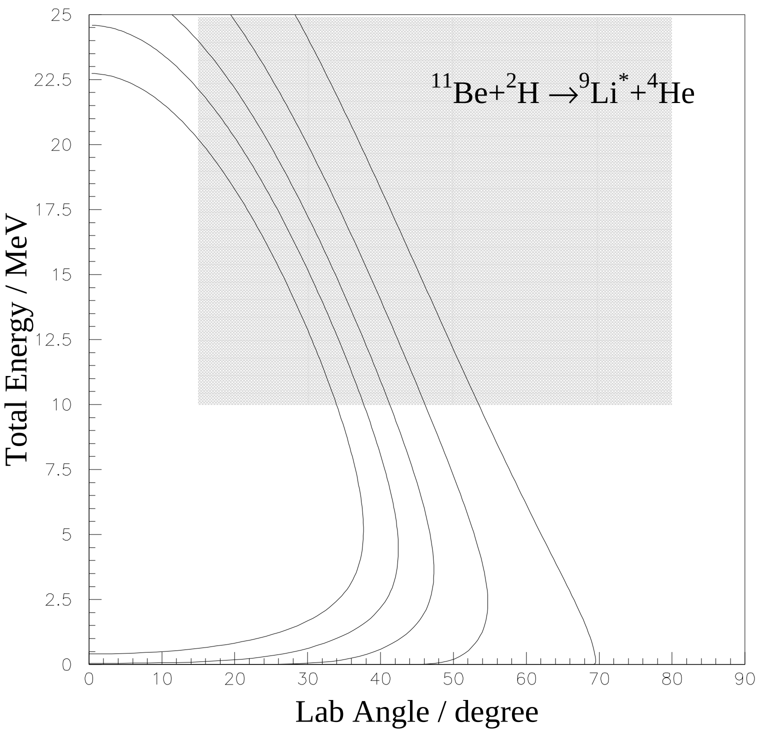

Figure 4: Kinematic curves for the ^{11}Be(d,α)^{9}Li reaction at 3.1 MeV/u going to final states at excitation energy 0, 2.691, 4.296, 5.380 and 6.430 MeV. The shaded square shows the region where reaction products can be identified.

in the target, can be extracted by measuring the beta-decay in thick Si-pad detectors placed on either side of the thick reaction target (see the setup in figure 5 in the end of this proposal).

4 The proposed production method and experimental set-up

For the production of ^{11}Be and ^{12}Be we propose to use a standard Ta roll-foil target, which we, for the ^{11}Be case, expect to give similar or even higher yields than a UC-target (7×10^{6} ions/μC). For the ^{12}Be beam we again expect the yield from a standard Ta roll-foil target to be higher than from a UC-target (1.5×10^{3} ions/μC) and probably less than 7×10^{3} ions/μC as seen from thin Ta foil targets. The yield of ^{12}Be from a standard Ta roll-foil target would most likely be sufficient for the proposed beam test. For both ^{11,12}Be we require the use of the ISOLDE laser ion source.

In the beam time applied for in this proposal we wish to use the second beam line equiped with our charged particle detections setup also used for our ^{9}Li experiment [1, 2] at REX-ISOLDE.

In the case of the ^{11}Be beam the setup will be improved by using two DSSSD telescopes as shown in the left part of figure 5 with 32×32 strips (twice the spatial resolution compared to the 16×16 strip DSSSD used in the ^{9}Li experiment [1, 2]). With the use of two DSSSD telescopes we will first of all double our solid angle coverage compared to our previous experiment at REX-ISOLDE but also introduce the possibility of measuring the light and heavy fragment in coincidence. This could improve the resolution on the measured excitation energy by using the invariant mass method. The two DSSSD telescopes should cover from 15° to 80° on either side of the beam direction, and would be composed

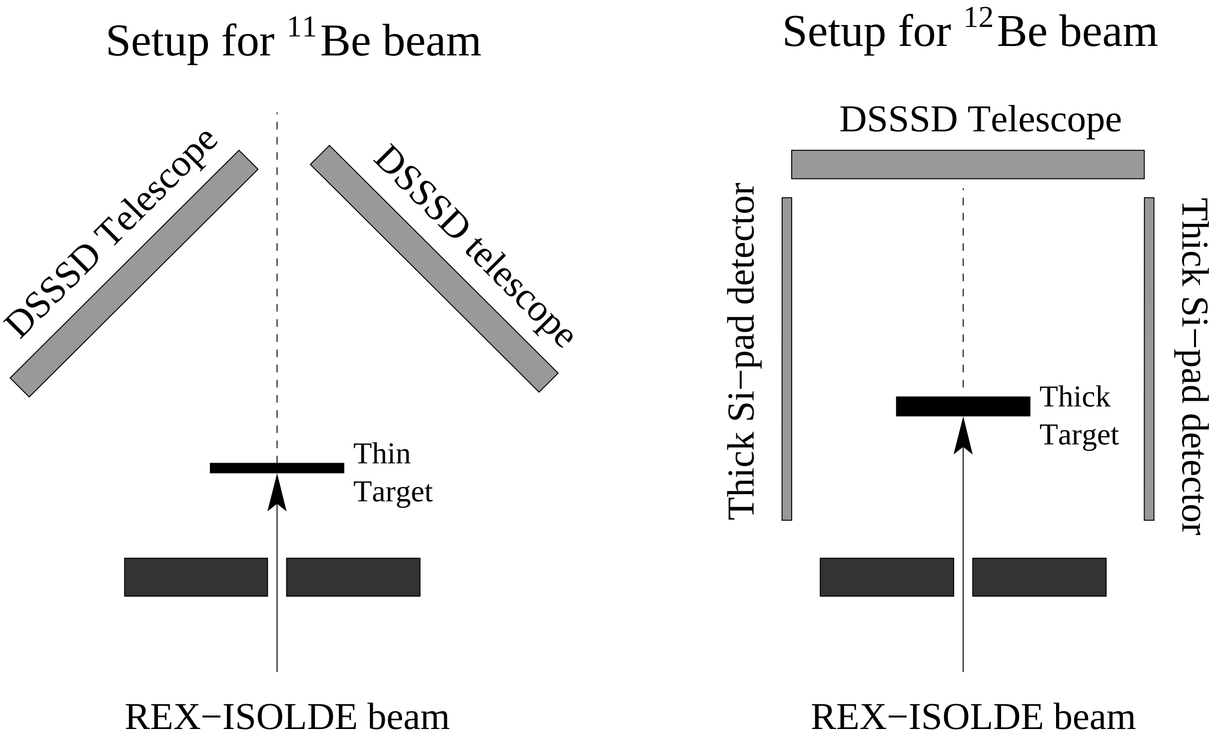

Figure 5: Setup for the proposed reactions with ^{11}Be (left) and ^{12}Be (right) beams at REX-ISOLDE.

of 60 μm DSSSDs and a 1.5 mm Si-pad detectors to allow for particle identification for p,d,t,^{4}He and ^{6}He above 2.3 MeV, 3 MeV, 3.5 MeV, 10 MeV and 11 MeV, respectively (as indicated in figures 1-4).

For the ^{12}Be beam test the setup would consist of one DSSSD telescope (same specifications as above) centered behind a thick Polyethylene target to measure elastical scattered protons from ^{12}C to monitor this contamination. On either side of the target thick Si-pad detectors (5×5 cm area, 1.5 mm thick) will be placed to detect beta-decay of ^{12}Be to provide the yield. This setup is shown in the right part of figure 5.

5 Summary and Beam request

The proposed reactions at 3.1 MeV/u with a ^{11}Be beam on a deuteron target is a unique possibility offered at ISOLDE, since this is the only ISOL facility where Be-beams are available. The experiments proposed here will add new information to topical issues such as vanishing of magic numbers, halo-states, and molecular states in the Be-isotopes.

We ask for **20 shifts** of radioactive beam for the ^{11}Be part, and **5 shifts** of radioactive beam for ^{12}Be to investigate the possibilities for producing a clean beam of this isotope. In addition we ask for **4 shifts** for stable beam adjustments, calibrations and beam changing at REX-ISOLDE. We also request to use the ISOLDE VME data acquisition and the CERN data storage system.

References

[1] H.B. Jeppesen *et al.*, submitted to Nucl. Phys. A.
[2] H.B. Jeppesen, Ph.D. thesis August 2004 and paper in preparation.
[3] U.C. Bergmann *et al.*, Eur. Phys. J. **A11** (2001) 279.

[4] H. Jeppesen *et al.*, Nucl. Phys. **A709** (2002) 119.
[5] R. Anne *et al.*, Nucl. Phys. **A575** (1994) 125.
[6] T. Nakamura *et al.*, Phys. Lett. **B331** (1994) 296.
[7] T. Aumann *et al.*, Phys. Rev. Lett. **84** 35 (2000).
[8] M. Chartier *et al.*, Phys. Lett. **B510** (2001) 24.
[9] J.S Winfield *et al.*, Nucl. Phys. **A683** 48 (2001).
[10] P. Palit *et al.*, Phys. Rev. **C68** (2003) 034318.
[11] J.A. Tostevin *et al.*, Phys. Rev. **C66** (2002) 024607.
[12] A. Shrivastava *et al.*, Phys. Lett. **B596** (2004) 54.
[13] W. Geithner *et al.*, Phys. Rev. Lett. **83** (1999) 3792.
[14] F. Barker, J. Phys. **G2** (1976) L45.
[15] A. Navin *et al.*, Phys. Rev. Lett. **85** 266 (2000).
[16] H.T. Fortune, G.-B. Liu and D.E. Alburger, Phys. Rev. **C50** 1355 (1994).
[17] H. Iwasaki *et al.*, Phys. Lett. **B491** 8 (2000).
[18] S. Shimoura *et al.*, Phys. Lett. **B560** 39 (2003).
[19] M. Freer *et al.*, Phys. Rev. Lett. **82** 1383 (1999).
[20] M. Freer *et al.*, Phys. Rev. **C63** 034301 (2001).
[21] Y. Kanada-Enyo and H. Horiuchi, Phys. Rev. **C68** 014319 (2003).
[22] T. Suzuki *et al.*, Phys. Rev. **C67** (2003) 044302.
[23] G. Martínez Pinedo, private communication (2004).
[24] A. Bonaccorso and N. Vinh Mau, Nucl. Phys. **A615** (1997) 245
[25] F.M. Nunes *et al.*, Nucl. Phys. **A703** (2002) 593.
[26] E. Garrido *et al.*, Phys. Lett. **B600** (2004) 208.
[27] K. Shima *et al.* Atomic data and nuclear data tables **51** 173 (1992).