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Interest in an ISOL beam of ^{8}B at ISOLDE

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Abstract

The possibility of making a beam of ^{8}B at ISOLDE is under discussion. Here we explore physics possibilities opened by such a beam at ISOLDE both for β-decay studies and reactions such as resonant elastic scattering and transfer reactions.

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1 Physics interest of ^{8}B

Apart form the possibility of employing ^{8}B as a neutrino source in the β-beam context this isotope is interesting both due to its β-decay and ground state structure.

The existence of so-called halo nuclei, characterized by an unusually large spatial extension, was recognized more than 20 years ago. The large spatial extension of halo nuclei is explained by the presence of one or two loosely bound valence nucleons with a large fraction of their wave function extending into the classically forbidden region. For the wave function of the valence nucleon to extend far into this region, the nucleon must be weakly bound, and Coulomb and centrifugal barriers must be small. This explains why nearly all halo nuclei have been found among the light neutron-rich nuclei.

^{8}B is the only nucleus known to possess a proton halo structure in its ground state [Jon04]. The proton separation energy is only 137 keV. The most compelling evidence for the halo structure of ^{8}B comes from $p + {}^7$Be breakup reactions at relativistic energies on carbon and lead targets [Sme99, CG02, CG03]. For more recent studies, see [Agu09, Fur09].

The halo structure of ^{8}B has implications for the ^{7}Be + p capture cross section at low energies. In the solar environment, the ^{7}Be + p reaction takes place at a center of mass energy of ~ 20 keV. The proton already encounters the Coulomb barrier at a separation of $\sim$50 fm, making the capture cross section highly sensitive to the tail of the ^{8}B ground-state wave function [Rii93]. Long the most uncertain rate in the *pp* chain, this cross section has recently been determined to an accuracy of 5% [Jun03, Jun10].

Our present understanding of the β decay of ^{8}B is that it occurs as a two-step process. First, the ^{8}B ground state decays to ^{8}Be by emitting a positron and an electron neutrino. Second, the unbound ^{8}Be nucleus breaks up in two α particles:

$$^8\mathrm{B} \rightarrow {}^8\mathrm{Be} + e^+ + \nu_e \ , \quad {}^8\mathrm{Be} \rightarrow \alpha + \alpha \ . \tag{1}$$

A schematic illustration is given in Fig. 1. Transitions from the 2^+ ground state of ^{8}B to the 0^+ ground state of ^{8}Be or the very broad 4^+ state at 11.4 MeV are second forbidden and hence strongly suppressed. A recent experimental study [Bac07] gives an upper limit of 7.3×10^{-5} for the branching ratio to the ground state. No 1^+ or 3^+ states are energetically accessible in positron decay. This means that the decay proceeds exclusively by allowed transitions to the 2^+ states. The majority of the decays proceed via the broad 3 MeV state, resulting in a broad distribution of α-particle energies peaked around 1.5 MeV.

The ^{8}B nucleus may also decay by capturing one of its atomic electrons (electron capture, EC). Close to the endpoint of the β-decay window, we find two 2^+ states at excitation energies of 16.626 and 16.922 MeV. These states are known to be nearly maximally mixed in isospin. We may therefore assume their β-decay matrix elements to be approximately equal. The lower state is situated 332 keV below the endpoint of the β-decay window; the upper state only 36 keV below.

The decay of ^{8}B has been intensely studied in recent years in order to extract precisely the neutrino spectrum from the decay, which can then be compared to measured spectra from the Sun.

A measurement of the decay of ^{8}B was performed by Ortiz *et al.* in 2000 [Ort00]. In their experiment, the ^{8}B activity was implanted in a thin carbon foil and the α particles were measured in coincidence in two Si detectors. A new measurement was performed by Winter *et al.* [Win03, Win06], who implanted ^{8}B ions into a 91 μm thick Si detector and measured the sum energy of the α particles. One advantage of their approach is the complete absence of insensitive layers of material in which the α particles lose energy.

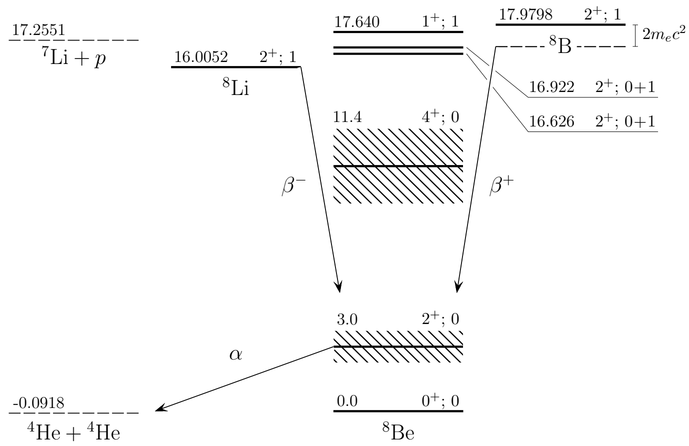

Figure 1: Nuclear levels in the $A = 8$ isospin triplet below the ground state of ^{8}B. The levels are labeled by their energy above the ^{8}Be ground state (in MeV), their spin-parity and their isospin.

One significant drawback is the systematic shift in energy of several tens of keV due to β summing which must be accounted for with simulations. In between the measurements of Ortiz *et al.* and Winter *et al.*, Bhattacharya *et al.* performed another measurement using a conventional single-α technique [Bha06]. The ^{8}B activity was here implanted in a thin carbon foil and the α particles detected in small solid-angle Si detectors to minimize β summing.

The results of Winter *et al.* and Bhattacharya *et al.* are in excellent agreement but disagree with the results of Ortiz *et al.* Winter *et al.* and Bhattacharya *et al.* find that the peak of the E_x distribution is narrower and occurs about 50 keV higher in energy than do Ortiz *et al.*

To resolve this discrepancy, our collaboration has recently performed two independent experiments in which the sum energy of the two α particles was measured by different techniques [Hyl10, Kir10]. The first experiment was performed in January 2008 at the ISOL facility IGISOL with a setup similar to that of Ortiz *et al.* The yield of ^{8}B at IGISOL was of the order of 300 ions per second. The α particles are measured in coincidence in separate detectors facing the thin carbon foil in which the ^{8}B activity is implanted. The second experiment was performed at the turn of the year 2008/2009 at the KVI facility in Groningen, The Netherlands, using an implantation technique similar to that of Winter *et al.* The setup was improved by using a 78 μm thick, finely segmented, Si detector with strips only 300 μm wide, whereby the effects of β summing were much reduced [Smi05].

In conclusion at the present time there is no obvious need for new precision measurements aiming for the neutrino spectrum.

2 Physics motivation for a ^{8}B beam at ISOLDE

2.1 Decay questions

The only excited state in ^{8}Be above the β-decay window energetically accessible in electron-capture decay, is the 1^+, $T = 1$ state at 17.640 MeV, see Fig. 1. It is situated 385 keV above the $p + {}^7$Li threshold and known to decay mainly by proton emission. We may estimate the EC decay rate to this state by picturing ^{8}B as composed of a proton loosely bound to a ^{7}Be core and assuming that the electron is captured on the ^{7}Be core with the proton acting merely as a spectator.

From the 53.22(6) day half-life of ^{7}Be and the 89.6% braching ratio to ground state of ^{7}Li, we deduce a capture rate of 1.4×10^{-7} s^{-1} to the ground state of ^{7}Li. (The first excited state in ^{7}Li at 478 keV accounts for the remaining 10.4%.) Assuming that the matrix element for electron capture is unaffected by the presence of the proton, we only have to account for the difference in phase space in the final state. For EC decays, the phase space is proportional to the neutrino energy squared. In the decay of ^{7}Be to the ^{7}Li ground state, the neutrino energy is 862 keV; in the decay of ^{8}B to the 17.640 MeV state in ^{8}Be, it is 340 keV. Therefore, our estimate of the EC decay rate is

$$r_{\mathrm{EC}} \sim 1.4 \times 10^{-7}\ \mathrm{s}^{-1} \times \left(\frac{340\ \mathrm{keV}}{862\ \mathrm{keV}}\right)^2 = 2 \times 10^{-8}\ \mathrm{s}^{-1}\ . \tag{2}$$

In comparison, the total decay rate of ^{8}B, deduced from its 770 ± 3 ms half-life, is 0.9 s^{-1}. The EC decay to the 17.640 MeV state in ^{8}Be has not previously been observed. A measurement of its strength would deepen our understanding of the halo structure of the ^{8}B nucleus. This would require of the order of 10^9 decays which in one week of beamtime corresponds to a yield of $2{\times}10^3$ ions/s. Note, this type of experiment is *only* possible with ISOL quality beams and can therefore not be carried out with existing beams.

For completeness we also mention that, since many years, the mirror decays of ^{8}Li and ^{8}B to ^{8}Be have been used to study the properties of the so-called "induced weak currents" in nuclei [Gre85] (only surpassed in popularity by the mirror decays of ^{12}B and ^{12}N to ^{12}C). Generally speaking, the term "induced weak currents" designates the modifications to weak processes occurring in nuclei due to the presence of strong interactions, implying that induced weak currents are sensitive to the underlying quark structure of the nucleons. The modifications are of recoil order, which is to say at the 10^{-3} level or below, and are best studied in relative measurements of mirror decays whereby effects of nuclear structure are minimized. More specifically, one compares the β^- and β^+ strength functions [Wil71], or one compares the form of the β-α angular correlations [Sum08]. See also [GM58, Wil00].

2.2 Reactions induced by a beam of ^{8}B.

If a sufficiently intense beam of ^{8}B at ISOLDE is achieved one can consider inducing reactions with REX-ISOLDE. Today secondary beams of ^{8}B already exist in the energy region of REX-ISOLDE with intensities of the order of several 10^4 ions/s [Agu09]. The beam quality at REX-ISOLDE will be better, but it is estimated that the beam intensity should at least be of the same order of magnitude to be interesting.

Here we give three suggestions for possible first experiments with an accelerated ^{8}B beam at ISOLDE:

1. Resonant elastic scattering on a thick proton (plastic) target. This type experiment is the least demanding in terms of needed beam intensity. The minimum accelerated beam needed is of the order of 10^3 ions/s. In this case we would study high-lying resonances in ^{9}C.
2. Rutherford scattering below the barrier on a heavy target. This type of experiments have been performed or are planned with neutron-halo beams of ^{11}Li and ^{11}Be. This physics is focused on the different roles of the core and halo in the scattering. Doing this with a proton halo opens new possibilities (first steps in this direction have

already been taken [Agu09]). The minimum beam is again rather low - somewhere in the region 10^{3-4} ions/s.

3. The reaction ^{8}B(d,p)$\alpha\alpha p$ populates a four-body final state with a Q-value of the order of 15 MeV. A detailed study would give information on properties of unbound states in ^{6}Be, ^{9}B and possibly ^{10}C as well as being a very exotic case of transfer to the continuum. Our collaboration have specialised in analysis techniques for this kind of studies [Alc09].

3 Summary

In conclusion, there are interesting prospects for a ^{8}B beam at ISOLDE. The least demanding opportunities in terms of required beam intensity are β-decay studies, while reaction studies are more demanding. If the development of a fast target for isotopes of Boron is achieved there are also very interesting possibilities with the more more neutron-rich isotopes $^{13-14}$B, but we delay the discussion of this until a beam of ^{8}B is prepared.

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