11Be(βp), a quasi-free neutron decay?

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Abstract

We have observed β\textsuperscript{−}−delayed proton emission from the neutron-rich nucleus 11Be by analysing a sample collected at the ISOLDE facility at CERN with accelerator mass spectrometry (AMS). With a branching ratio of (8.4 ± 0.6) × 10\textsuperscript{−6} the strength of this decay mode, as measured by the B\textsubscript{CT}-value, is unexpectedly high. The result is discussed within a simple single-particle model and could be interpreted as a quasi-free decay of the 11Be halo neutron into a single-proton state.

Keywords: beta decay, halo nucleus, 11Be

1. Introduction

Beta-minus decay and proton emission take a nucleus in almost opposite directions on a nuclear chart, so β\textsuperscript{−}−delayed proton emission (where beta decay feeds excited states that subsequently emit a proton) is forbidden in all but a few nuclei where it is heavily suppressed as the available energy is \( Q_{\beta p} = 782 \text{ keV} - S_n \) where \( S_n \) is the neutron separation energy of the nucleus. We describe here an experiment to detect this decay mode from the one-neutron halo nucleus 11Be that is believed to be the most favourable case due to the single-particle behaviour of halo nuclei that may favour this decay mode and due also to the relatively long half-life that is caused by the normal beta-decay of 11Be being hindered since a level inversion gives it a 1/2\textsuperscript{+} ground state rather than a 1/2\textsuperscript{−}.

Beta-delayed particle emission is in general a prominent decay mode for nuclei close to the dripline, see \cite{r22, r24} for recent reviews. The energetically open channels for 11Be are \( \beta\alpha \), \( \beta\tau \), \( \beta\pi \) and \( \beta\beta \) with corresponding Q-values of \( [2] \) 2845.2 ± 0.2 keV, 285.7 ± 0.2 keV, 280.7 ± 0.3 keV and 55.1 ± 0.5 keV. The low decay energy implies that the branching ratio for beta-delayed proton emission is low, typical estimates are slightly above 10\textsuperscript{−8}. To detect the process experimentally, it is therefore essential to keep contaminants at a very low level.

The \( \beta\pi \) decay mode may be expected preferentially in one-neutron halo nuclei, partly due to the requirement of low neutron separation energy, partly due to the more pronounced single-particle behaviour of halo nuclei. Two-neutron halo nuclei are in a similar way candidates for beta-delayed deuteron emission, which has so far been observed only in the nuclei 6He and 11Li \cite{r22, r10}. For 11Li the decay has a branching ratio of order 10\textsuperscript{−4}, the low value again caused by a small energy window, whereas cancellation effects reduces the branching ratio for 6He down to the 10\textsuperscript{−6} level. It may be more useful to consider the standard measure for the strength of a decay, the reduced matrix element

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squared $B_{GT}$, that is found from the relation

$$ f t = \frac{K}{g_f^2 B_F + g_A^2 B_{GT}} \quad (1) $$

where $f$ is the beta-decay phase space, $K/g_f^2 = 6144.2 \pm 1.6$ s and $g_A/g_f = -1.2694 \pm 0.0028$. Converting the observed spectra for beta-delayed deuteron emission from the two-neutron halo nuclei $^6$He $^{11}$ and $^6$Li $^{12}$ gives total $B_{GT}$ values within the observed energy range of about 0.016 and 0.75. (Note, however, that the $^6$He decay to the $^6$Li ground state has been described as an effective di-neutron to deuteron decay, it is a super-allowed transition with a $B_{GT}$ of 4.7. This may be a reflection of a general trend for super-allowed decays to occur in very neutron-rich nuclei $^{13}$.) For comparison, the sum of $B_{GT}$ for all currently known transitions in the $^{11}$Be decay is 0.27.

2. The experiment

2.1. General remarks

The radioactive $^{11}$Be nuclei were produced at the ISOLDE facility at CERN. Searching for protons with a kinetic energy of a few hundred keV with relative intensity $10^{-8}$ is challenging in a radioactive beam environment, so we instead detect the decay product, $^{10}$Be with a half-life of $1.5 \cdot 10^6$ y, that exists only in minute quantities on earth. To reach the needed sensitivity we must employ state-of-the-art AMS. It is also crucial to limit the amount of contaminants in the samples so sample collection took place at ISOLDE’s high-resolution mass separator. The resolution from the magnetic separation stage is supplemented by the electrostatic beam transport at ISOLDE similar to, but at lower resolution than, the separation stages in AMS facilities. A first attempt was made in 2001 and the results were published recently $^{[8]}$. The signal was not sufficiently strong to be clearly separated from background and gave a $\beta p$ branching ratio of $(2.5 \pm 2.5) \cdot 10^{-6}$, significantly above the published theoretical expectations. Due to improvements both in production of $^{11}$Be and AMS detection of $^{10}$Be, the current collection was performed in December 2012 and resulted in three samples.

2.2. Sample collection

The $^{11}$Be activity was produced by bombarding a UC target with 1.4 GeV protons. The products were ionized in a laser ion source, which provided element selectivity, mass separated in the ISOLDE high-resolution separator, and guided through several collimators to the collection point where they were implanted at 60 keV in a small copper plate (15$\times$20$\times$2 mm). A high-purity coaxial Ge-detector placed 40 cm downstream behind a lead shielding monitored the collection rate. The Ge-detector was energy and efficiency calibrated with standard sources of $^{60}$Co, $^{152}$Eu and $^{228}$Th. The main lines in the $\gamma$ spectrum recorded during $^{11}$Be collection are the 2124 keV line from the decay of $^{11}$Be and the 511 keV line from positron annihilation. The overall efficiency at 2124 keV is found to be $(2.0 \pm 0.2) \cdot 10^{-5}$. A second line from the decay at 2895 keV was also used to check the overall amount of $^{11}$Be. The two determinations gave about the same precision, the one from the 2124 keV line being dominated by systematic uncertainties in the efficiency and the one from the 2895 keV being dominated by statistical uncertainties, and were internally consistent leading to a final value for the amount of collected $^{11}$Be in the main sample (S1) of $(1.447 \pm 0.055) \cdot 10^{12}$. This includes a correction for dead time of 2.8%, determined from the ratio of accepted to total number of triggers.

As cross-checks two other samples were collected: sample S2 at the mass position of $^{11}$Li (0.02 mass units heavier than $^{11}$Be) where an upper limit of $3 \cdot 10^6$ could be determined for the number of atoms collected (corresponding to a $^{11}$Li yield below 625/s which is reasonable) and, for one second only, sample S3 at the $^{10}$Be mass position where an estimate of the current of 3.5 pA (uncertain by a factor two) converts into $2 \cdot 10^7$ atoms. According to SRIM calculations $^{[14]}$ about 6% of all Be ions implanted in Cu at 60 keV energy will backscatter out of the sample. Most of the backscattered ions are expected to remain close to the sample so $\gamma$-rays from their decays will be seen as well, although the decay products are not retained in the sample. This gives a correction which we estimate to be $4 \pm 4\%$.

2.3. Accelerator mass spectrometry

The $^{10}$Be accelerator mass spectrometry (AMS) measurements were performed at the Vienna Environmental Research Accelerator (VERA) at the University of Vienna. VERA is a dedicated AMS facility based on a NEC 3 MV pelletron tandem accelerator. A new scheme for $^{10}$Be using a passive foil absorber in front of a gas ionization chamber detector was employed. In this way the detection efficiency for $^{10}$Be atoms is increased significantly.
According to TRIM simulations \cite{14} the maximum implantation depth of $^{11}$Be in our copper plate catcher was below 1 µm. To reduce the amount of material to be dissolved only the surface layer of each irradiated copper plate was leached in nitric acid. A second leaching was performed to verify the blank level of the irradiated copper plate. The second leaching of sample S3 did not produce enough BeO for a measurement. For samples S1 and S2 the values of the second leachings were consistent with a blank sample. This shows that the material was sitting in the surface, as expected for an implanted sample, and not due to a bulk contamination. An amount of 359 µg (uncertainty 3\%) $^9$Be carrier was added to the solution to reach a $^{10}$Be/$^{9}$Be isotopic ratio in the range of $10^{-16}$–$10^{-11}$. In the next step the solution was treated with ammonium hydroxide to precipitate the beryllium as beryllium hydroxide (Be(OH)$_2$). The dissolved copper remains in the solution in this step. The beryllium hydroxide was dried out by heating in an oven at 900°C for at least 8 hours forming beryllium oxide (BeO). The BeO powder was mixed 1:1 with high purity copper powder and pressed into sample holders and mounted together with standard and blank material in a MC-SNICS type Cesium sputter ion source. Blank is the pure phenakite material directly pressed into a sample holder. A separate sample, S-blank, went through the chemistry preparation to check for the amount of $^{10}$Be introduced during the chemical sample preparation. BeO$^-$ was extracted from the ion source and stripped in the terminal of the tandem accelerator to Be$^{2+}$, resulting in a total ion energy of 2.4 MeV. After further mass separation by a sector magnetic analyzer and an electrostatic analyzer the remaining particles are sent to a gas ionization chamber detector with a two-split anode for particle identification. A silicon nitride foil stack as a passive absorber was installed in front of the detector. This foil stack prevents the isobaric background $^{10}$B from entering into the detector: The energy loss of boron in the foil stack is slightly larger compared to beryllium. By selecting the right foil thickness and carefully tuning the particle energy the boron ions are stopped in the foil stack whereas the beryllium ions can enter the detector.

The final results are given in table \ref{tab:act}. The amount of atoms in sample S3 agrees with the estimation from the implantation current. The number for sample S2 is consistent with the lack of observed γ-rays from the decay of $^{11}$Li. The number for sample S1, the $^{11}$Be sample, is $(1.170 \pm 0.047) \cdot 10^7$.

### Possible contaminants

Contaminations in our sample might arise due to tails of the neighbouring activities $^{10}$Be or $^{11}$Li, whose decay also produces $^{10}$Be. Both possibilities are ruled out by the low recorded number of atoms for the $^{11}$Li sample (S2). The ISOLDE mass separator profile was found by measuring the beta activity as the mass settings were changed around the nominal $^{11}$Be mass, see figure \ref{fig:mass}. The release function of this specific target and ion source combination was measured first, which allows to combine measurements with different collection times relative to

\begin{table}[ht]
\caption{Results of the AMS measurement. S1 to S3 denote the irradiated samples. 1st and 2nd correspond to the first or second leaching. Blank and S-blank are control samples without activity.}
\centering
\begin{tabular}{lccc}
\hline
Sample & $^{10}$Be/$^{9}$Be ratio & $^{10}$Be atoms \\
\hline
S1-1st & $(4.87 \pm 0.13) \cdot 10^{-13}$ & $(1.17 \pm 0.05) \cdot 10^4$ \\
S1-2nd & $(1.26 \pm 0.56) \cdot 10^{-15}$ & $(3.03 \pm 1.35) \cdot 10^4$ \\
S2-1st & $(3.10 \pm 0.94) \cdot 10^{-15}$ & $(7.45 \pm 2.27) \cdot 10^4$ \\
S2-2nd & $(4.4 \pm 3.1) \cdot 10^{-16}$ & $(1.06 \pm 0.75) \cdot 10^4$ \\
S3-1st & $(1.54 \pm 0.03) \cdot 10^{-12}$ & $(3.70 \pm 0.13) \cdot 10^7$ \\
S-blank & $(4.9 \pm 3.4) \cdot 10^{-16}$ & $(1.18 \pm 0.82) \cdot 10^4$ \\
blank & $(1.3 \pm 1.3) \cdot 10^{-16}$ & $(3.12 \pm 3.12) \cdot 10^3$ \\
\hline
\end{tabular}
\label{tab:act}
\end{table}

\begin{figure}[ht]
\centering
\includegraphics[width=0.5\textwidth]{mass_scan.png}
\caption{Mass scan of the ISOLDE high-resolution separator across the $^{11}$Be position. The beta activity measured is shown versus the mass with positions indicated for $^{11}$Be and the possible contaminant $^{11}$Li. The horizontal line marks the detection limit of 0.2/s.}
\label{fig:mass}
\end{figure}
proton impact on target. In this way the sensitivity was increased and the activity could be followed down to the $10^{-5}$ level that occurred at a mass difference of 0.05 mass units. The only remaining way for $^{10}$Be to appear on the $^{11}$Be position is as the molecule $^{10}$Be$^1$H, but this molecule is unlikely to be formed in the target and to survive through the laser ion source since its ionization energy of 8.22 eV \cite{15} is much higher than its dissociation energy of 3.26 eV. Nevertheless, we have re-checked the data from an earlier experiment on $^{12}$Be \cite{16} and were able to put limits on the amount of $^{11}$Be$^1$H (from the $\beta^0$ branch) that would correspond in our current case to a $^{10}$Be$^1$H intensity less than $2 \cdot 10^{-6}$ of $^{11}$Be. Our conditions should be better, partly due to higher laser ionization power, partly due to the beam passing through a gas-filled RFQ cooler, both effects that would enhance molecular breakup. We therefore conclude that we have observed the $^{11}$Be($\beta p$) decay via detection of the final nucleus $^{10}$Be. The observed intensity converts to a branching ratio of $(8.4 \pm 0.6) \cdot 10^{-6}$.

3. Discussion

The experimentally found branching ratio is surprisingly large, but consistent with the outcome of the first experiment. If the strength in $^{11}$Be($\beta p$) was as broadly distributed as in $^{11}$Li($\beta d$), we would expect the $B_{\text{GT}}$ within the Q-window to be less than 0.1, which would not be sufficient to explain the decay rate. We therefore turn to a simple model for the decay along the lines of the direct decay calculations in \cite{2,17} details of the calculations are reported elsewhere \cite{18}.

The basic assumption is that the beta decay proceeds as an essentially detached decay of the halo neutron into a proton. The initial and final state wavefunctions are calculated as single-particle states in square-well or Woods-Saxon potentials with the final state spectrum discretized by imposing a large confining radius at 1000 fm. The overlap of the wavefunctions gives the beta strength $B_{\text{GT}}$ and the decay rate is found from equation (11).

The final total branching ratio for beta-delayed proton emission depends strongly on the strength of the potential between the final state proton and $^{10}$Be. For most potential strengths the branching ratio will indeed be a few times $10^{-8}$, as in other calculations, but in a limited range the beta strength will be concentrated within the Q-window. Effectively, in this range the proton formed in the decay interacts strongly with the remaining $^{10}$Be and forms a resonance-like structure; as a consequence it emerges with a quite well defined energy. The branching ratios obtained for this set of parameters are shown in figure 2 as a function of the energy of the resonance.

The simple model neglects isospin. The lowest $T = 3/2$ states are situated slightly more than 1 MeV above the $Q_{\beta p}$ window. They are members of isospin multiplets that include the $^{11}$Be ground state and first excited state neutron halos. The data indicate \cite{19} that the intermediate states ($|T_\pi|$ of 1/2) in these multiplets have good total isospin rather than a composition with just one proton (or neutron) plus core. We therefore expect that realistic final state wave functions in our case, with $T = 1/2$, also should have good isospin. Standard isospin coupling then predicts that the state should be proton plus $^{10}$Be with weight 2/3 and neutron plus $^{10}$Be($T=1$) with weight 1/3. Our calculated decay probabilities must therefore be corrected by a factor 2/3. A further reduction factor about 0.7 is due to the initial $^{11}$Be wavefunction containing several configurations \cite{20}. The overall scaling factor on the theory, included in figure 2 is therefore about 0.5.

Could this be an established resonance in $^{11}$B?
of the halo neutron in $^6$He into a single-proton state. This appears to be a simpler process than the $\beta d$ decays of the two-neutron halo nuclei $^4$He and $^{11}$Li. Although the halo structure must be important for the $\beta p$ decay mode, the large value of $B_{GT}$ may be related to large values found in other (non-halo) near-dripline nuclei $^{11}$Li and point to a more widespread change of beta-decay patterns at least in light nuclei in line with some predictions.$^{23}$

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