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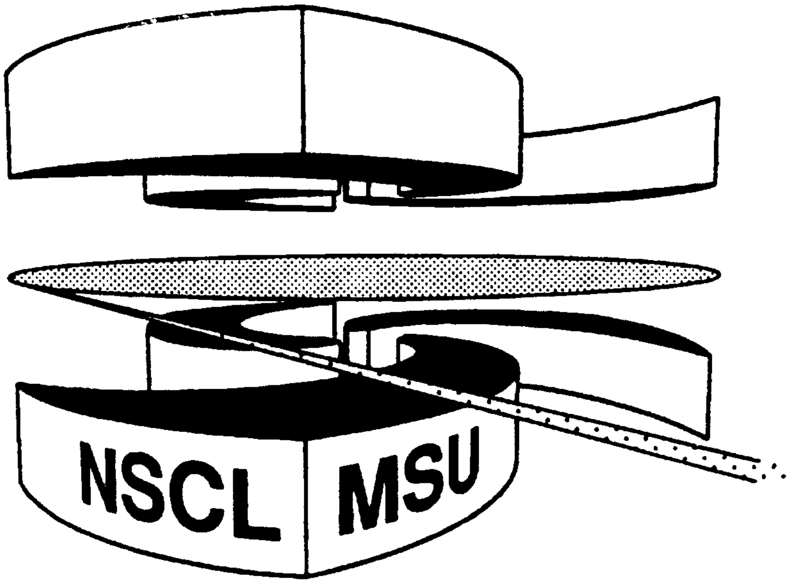

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# MASS MEASUREMENTS BEYOND THE DRIPLINES

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Particle unstable nuclei were studied using fragmentation reactions and single nucleon transfer reactions with radioactive beams. Relative decay energies of the neutron unstable nuclei $^{10}$Li and $^{13}$Be were measured and states which decay by the emission of a very low-energy neutron were observed in both cases. On the proton rich side evidence for a state below the presently accepted ground state of $^{11}$N was found.

## 1. INTRODUCTION

The structure of nuclei along the proton and neutron driplines yields new insights into the properties of nuclear matter and provides unique tests for nuclear structure models. The study of these nuclei is not limited to nuclei inside the dripline with relatively long lifetimes ($>10^{-7}$s), but can also be extended *beyond* the dripline where the lifetimes can be extremely short ($<10^{-20}$s). However, these nuclei are difficult to study because only the lightest nuclei are accessible with stable beams and even those involve multiple particle transfer reactions with very small cross sections.[1]

The detailed understanding of unstable nuclei along the neutron dripline is very important for the understanding of the neighboring halo nuclei. For example the knowledge of the n + $^{9}$Li potential is crucial for the three-body models of $^{11}$Li.[2-4] The two-neutron separation energy and the relative wave function of $^{11}$Li could only be reproduced simultaneously with significant contributions of s-wave strength in $^{10}$Li.[5] Recent calculations[6,7] also predict similar s-wave strength at low decay energies in $^{13}$Be crucial for the halo structure of $^{14}$Be.[8] We present new measurements of $^{10}$Li and $^{13}$Be. These neutron rich nuclei were populated via the fragmentation of $^{18}$O and the decay energy was deduced from the relative velocity of the neutron and the fragment.

One of the most interesting aspects of particle unstable nuclei at the proton dripline is the possibility to search for ground-state proton[9] and even ground-state two-proton radioactivity.[10] In heavy nuclear systems the Coulomb barriers are large and ground-state proton radioactivity has been observed.[9,11,12] However, the search for ground state two-proton radioactivity has been unsuccessful.[13,14] Two-proton emitters can decay through different competing channels, for example sequential proton decay or correlated di-proton ($^{2}$He) emission. A recent measurement of the two-proton decay of $^{12}$O determined an upper limit on the di-proton emission contribution of 7%.[15] This small branching ratio is not consistent with the large decay width of $^{12}$O. The branching ratio depends critically on the ground state energy of the intermediate state of $^{11}$N. However, the predicted ground state of $^{11}$N has never been measured and was only deduced from the mirror nucleus $^{11}$Be.[16,17] We produced $^{11}$N with the one-neutron stripping reaction from a radioactive beam of $^{12}$N.

## 2. NEUTRON UNSTABLE NUCLEI

The nuclei beyond the neutron dripline were produced in a fragmentation reaction and the decay parameters were measured using the method of sequential neutron decay spectroscopy (SNDS) at 0°.[18]

A schematic of the experimental setup is shown in Figure 1. A 94 mg/cm$^{2}$ $^{9}$Be target was bombarded with an 80 MeV/nucleon $^{18}$O beam from the K1200 cyclotron of the National Superconducting Cyclotron Laboratory. The scattered beam and the fragments of interest were separated by a quadrupole/dipole combination. The fragments were identified with a triple $\Delta E$ - E, silicon-CsI telescope. The velocity of the fragments was calculated from the energy in the CsI with an energy resolution of

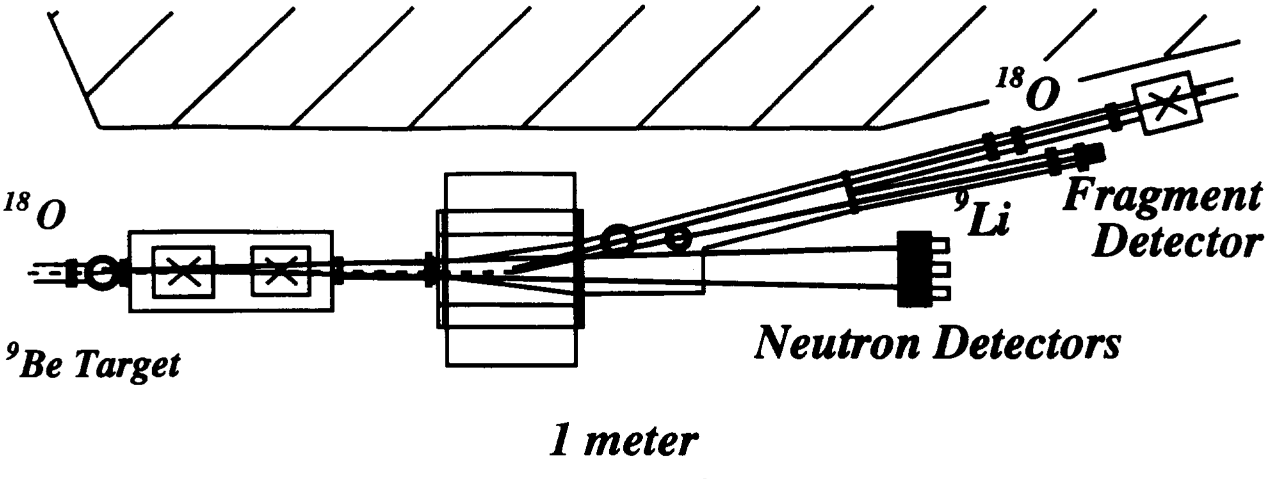

Figure 1: Experimental set-up for the sequential neutron decay spectroscopy measurements. Details are explained in the text.

~0.7%. In addition, a thin fast plastic detector measured the timing of the fragments. The neutrons were detected in five liquid scintillators positioned at 0° at a distance of 6 m. The neutron velocity was derived from the time-of-flight measurements with respect to the fragment time (corrected for the fragment time-of-flight). The relative velocity $v_{rel} = v_n - v_F$ is directly related to the decay energy of the initial system: $E_{res} = \frac{1}{2}\mu v_{rel}^2$, where $\mu$ is the reduced mass of the neutron and fragment system.

The present method has the advantage that the dipole selects all produced fragments with the same mass-to-charge ratio ($M/Q$) because the velocity of the fragments is similar. The magnets were tuned to select $M/Q = 3$ and thus it is possible to measure the decay of $^7$He, $^{10}$Li and $^{13}$Be simultaneously, where the $^7$He serves as a calibration reaction.

Figure 2 shows the relative velocity spectra for the decay of $^7$He and $^{10}$Li. The solid line represents a preliminary simulation for the $^7$He decay which was calculated using the known ground state parameters of $E_{res}$ = 450 keV and $\Gamma$ = 160 keV.[19] The background was estimated with a Gaussian line shape. The analysis was essentially identical to the one described in Reference 20. The resolution of the present experiment was significantly better than in the previous experiment. The resolution improved from ~ 150 keV to ~ 90 keV at 450 keV (the resonance energy of $^7$He).

The relative velocity spectrum of the decay of $^{10}$Li shows a central peak, indicating a state which decays by the emission of very low-energy neutrons. This state could correspond to an s-wave ground-state of $^{10}$Li, which had been suggested theoretically.[21] Previous measurements of the mass of $^{10}$Li with multiple particle

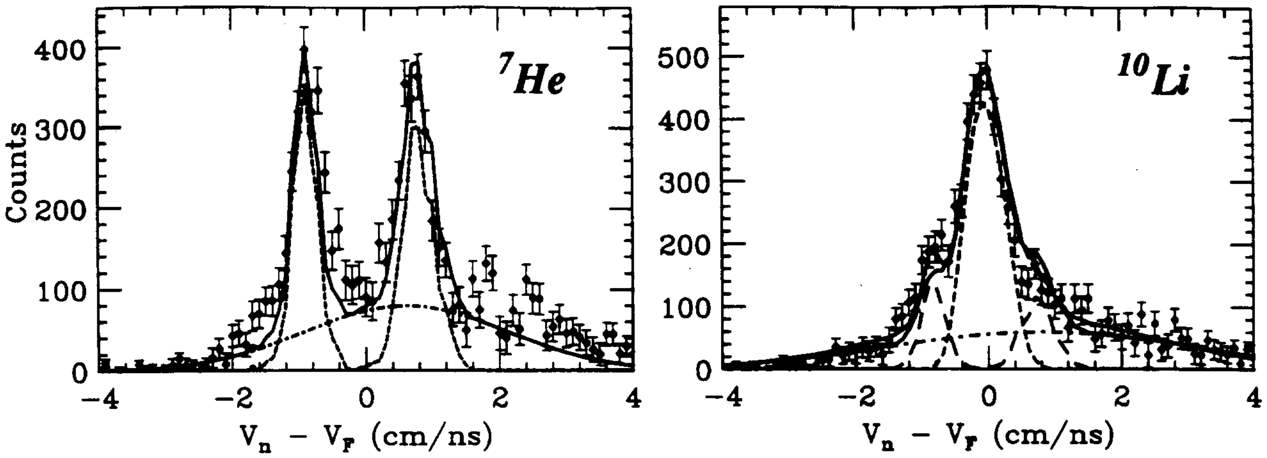

Figure 2: Relative velocity spectra for neutrons in coincidence with $^6$He (left) and $^9$Li (right). The fit for the decay of $^7$He (n +$^6$He) was performed with the known ground state values of $^7$He. The $^{10}$Li spectrum includes a calculation with a low decay energy (50 keV, short-dashed) and a high decay energy (420 keV, long-dashed).

transfer reactions and pion absorption yielded decay energies of 800±250 keV,[22] 420±50 keV,[1] and 150±150 keV,[23] respectively. Evidence for confirmation of the low lying s-wave has been reported recently.[24]

The central peak shown in Figure 2 appears to be narrower compared to the first published results[20] due to the improved resolution, allowing for a more accurate measurement. In addition to the central peak around zero relative velocity an enhancement around ±1 cm/ns is apparent. A preliminary analysis with the parameters used in Figure 2 of Reference 20 for a low decay energy ($E_{res}$ = 50 keV, $\Gamma$ = 100 keV) as well as a decay energy of 420 keV is included in Figure 2. The new values for the improved resolutions were used and the parameterization seems to overpredict the width of the central peak, indicating that the inherent width of the state is narrower and/or the decay energy is even smaller. Further detailed analysis will be able to extract more stringent limits on the energy and width of this state.

However, an inherent insufficiency of the method of SNDS is the fact that only the decay energy is measured and not the absolute energy of a state. Thus, in addition to the assumed scenario of a ground state decay of $^{10}$Li, it cannot be ruled out that the central peak corresponds to a decay from an excited state in $^{10}$Li (~ 2.4 MeV, assuming the ground state to be unbound by 420 keV) to the first (and only bound) excited state in $^9$Li (at 2.7MeV).

In addition to the decay of $^{10}$Li, the isotopic resolution of the fragment detector in the most recent experiment was sufficient to extract the decay of $^{13}$Be into $^{12}$Be

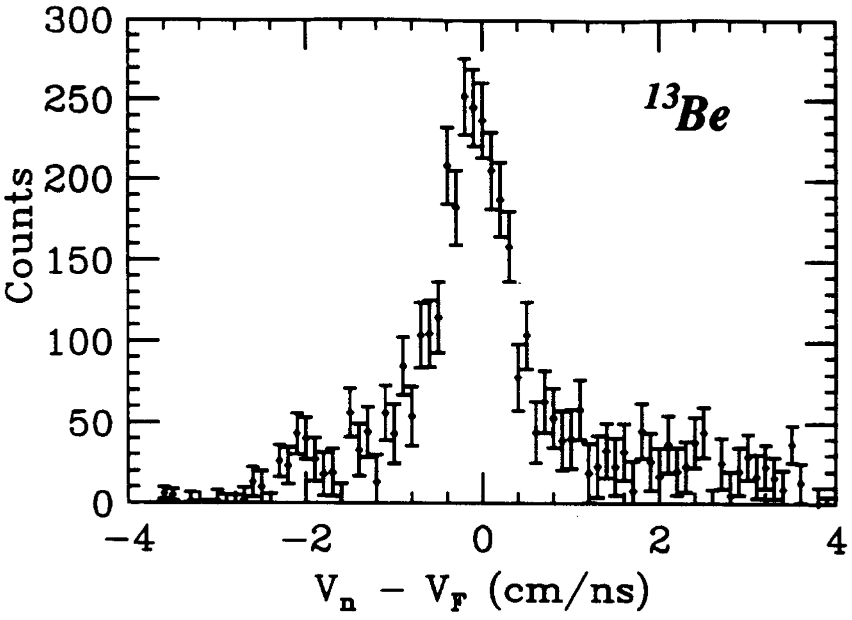

Figure 3: Relative velocity spectrum for neutrons in coincidence with $^{12}$Be. The single central peak indicates a state with a low decay energy in $^{13}$Be.

and a neutron. The relative velocity spectrum for this decay is shown in Figure 3, Again a central peak indicates a decay with the emission of a low energy neutron.

Similar to $^{10}$Li, it has been suggested that $^{13}$Be should have a low-lying s-wave resonance[6,7] which would explain the halo structure of $^{14}$Be.[8] However, so far no evidence for such a state has been observed.[6,25] The measured state is assumed to be $5/2^+$ and unbound by 2 MeV, although recently a state unbound by 900 keV was reported.[26] The observed peak around zero relative velocity could correspond to the decay of this $5/2^+$ state to the first excited state of $^{12}$Be, which is located at 2.1 MeV, thus resulting in a very small relative decay energy. A small branch of this state direct to the ground state of $^{12}$Be might be visible at 2 cm/ns in the spectrum. However, it could also correspond to the predicted low-lying s-wave strength which then would be a $^{13}$Be ground-state to $^{12}$Be ground-state decay.

A detailed analysis of the data is in progress and it might be possible to distinguish the two decay schemes.

## 3. PROTON UNSTABLE NUCLEI

In a recent experiment performed at the NSCL we searched for evidence of a di-proton component in the decay of $^{12}$O.[15] Figure 4 shows the decay scheme for $^{12}$O. With the presently accepted level scheme of $^{11}$N included in the Figure, $^{12}$O is

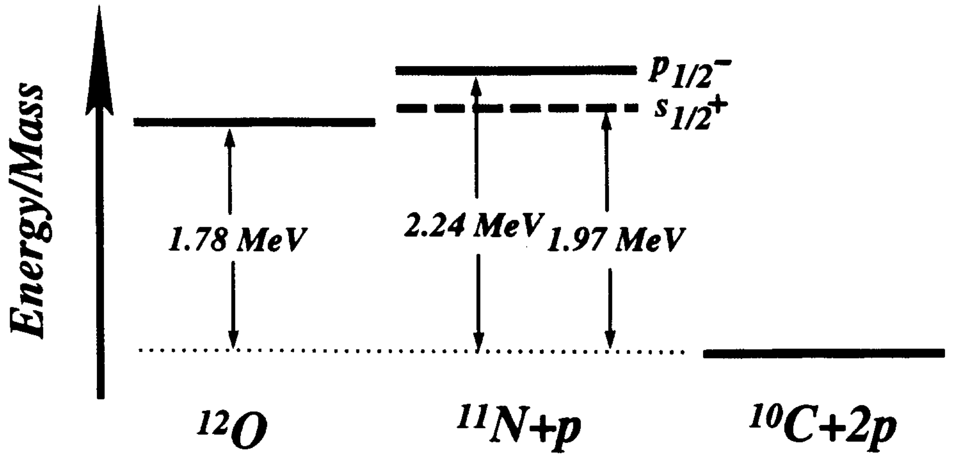

Figure 4: Decay scheme of $^{12}$O. The only measured state in the intermediate system $^{11}$N was assigned to be the $p_{1/2}^-$, whereas the $s_{1/2}^+$ was only deduced from the isobaric mass multiplet equation.

bound with respect to one-proton emission, but unbound with respect to two-proton emission. This seems to be essential for the possibility to observe correlated di-proton ($^2$He) emission. For all presently known cases of two-proton emitters, the one-proton decay channel is energetically available and the decay indeed proceeds sequentially.[27]

The $^{12}$O was produced via the one-neutron stripping/transfer reaction from a radioactive secondary beam of $^{13}$O. The two protons were detected in coincidence with the $^{10}$C fragments and all the energies and angles were measured. Thus, the decay energy and the opening angle distribution between the two protons in the center of mass system could be reconstructed as shown in Figure 5. The previously measured decay energy (1.79±0.04 MeV) and width (400±250 keV)[16,17] of the $^{12}$O ground state were reproduced. The opening angle between the two protons showed no evidence for contributions from a correlated di-proton emission (dashed) but was consistent with an isotropic emission in the center of mass system (solid). This observation is however inconsistent with a sequential decay scheme via the tail of the ground state of $^{11}$N. Due to the Coulomb barrier this decay mode is strongly suppressed and can not explain the large decay width of $^{12}$O.

The exact location of the $^{11}$N ground state is absolutely crucial for the determination of the decay characteristics of $^{12}$O. So far the location of only one state has been reported in $^{11}$N.[28] This state at 2.24 MeV with respect to $^{10}$C + 2p was interpreted as being $p_{1/2^-}$ and, in analogy to the mirror nucleus $^{11}$Be, to be the first excited state. The $s_{1/2^+}$ ground state at 1.97 MeV was actually only deduced from the isobaric mass

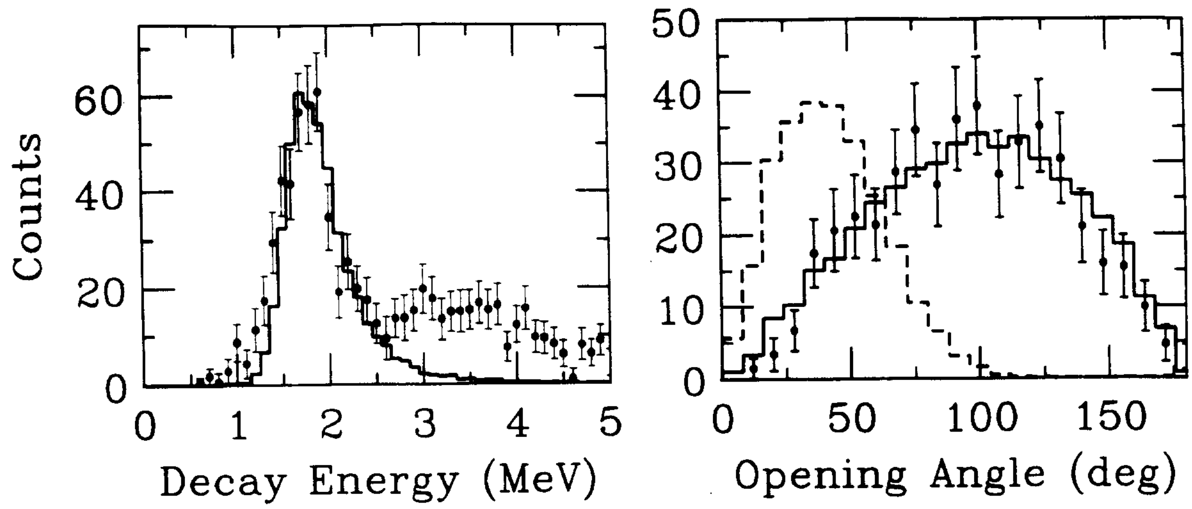

Figure 5: Distribution of the decay energy and the opening angle between the two protons for the decay of $^{12}$O (adapted from Reference 15).

multiplet equation (IMME) and has never been measured.[28,16] However, very recent calculations predict this state to be at a significantly lower energy. While Sherr *et al.*[29] locate the state between 1.1-1.5 MeV, Fortune *et al.*[30] predict 1.60±0.22 MeV. A new measurement of $^{11}$N using the multiple particle transfer reaction ($^{3}$He,$^{6}$He) observed several states but the decay energies were not determined.[31]

We measured the decay structure of $^{11}$N with the single neutron stripping/transfer reaction from the radioactive beam of $^{12}$N. The experimental conditions were very similar to the reaction producing $^{12}$O.[15] In the present case the $^{10}$C fragments were detected in coincidence with single protons. The fragments were detected at 0° with a PPAC plus $\Delta$E-E telescope at a distance of 62 cm. The PPAC yielded the position information and the energy was measured with a 3 mm thick Si(Li) detector. The protons were detected with the Maryland Forward Array at 20cm, which consists of an annular 300 $\mu m$ thick silicon detector backed by 16 Phoswich $\Delta$E-E plastic detectors to measure the proton energy. The decay energy of $^{11}$N can then be reconstructed from the proton and $^{10}$C energies and the opening angle between the two particles.

Figure 6 shows the decay energy spectrum of $^{11}$N. In a preliminary analysis the data were fitted with a simulation that included the experimental efficiencies, detector resolutions, and beam characteristics. It is apparent that the data can not be explained with the previously observed state at 2.24 MeV ($\Gamma$ = 740 keV, long-dashed) alone. At higher energies we added strength around 4 MeV ($\Gamma$ = 1 MeV, dot-dashed), although the interesting excess remains at lower energies. This state is significantly below the

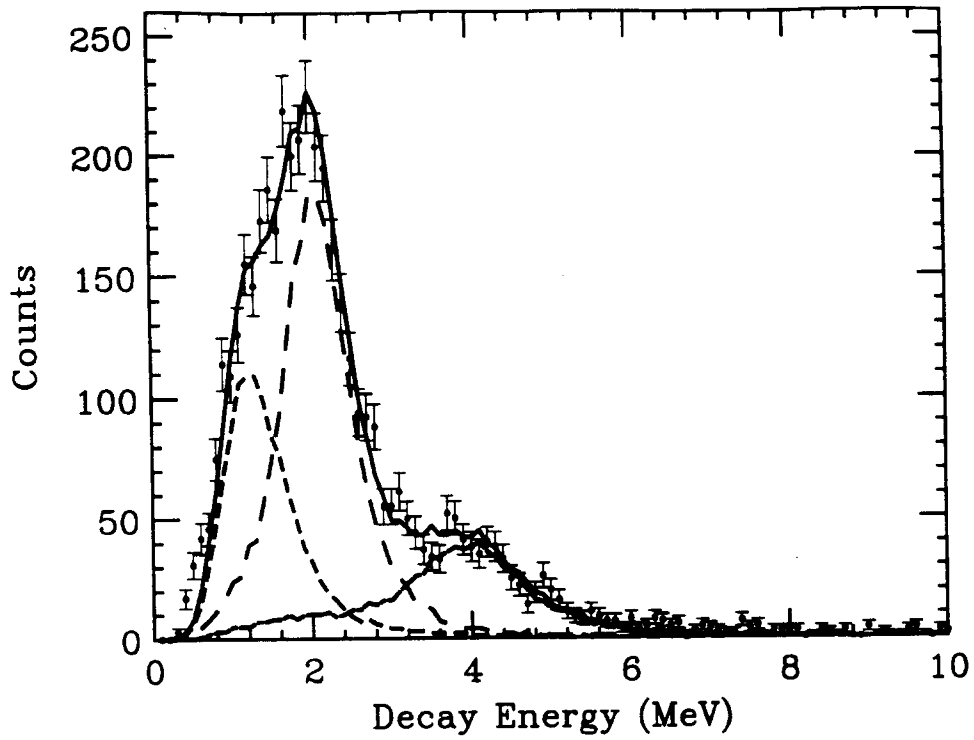

Figure 6: Decay energy spectrum of $^{11}$N. The individual contributions to the fit are explained in the text.

previously assumed $s_{1/2}$- ground state of 1.9 MeV. In order to achieve the overall fit to the data, we included a state at 1.2 MeV with a width of 1 MeV (short-dashed). However, this value is still very preliminary because barrier penetration, which becomes important at lower energies has not yet been included in the simulation.

## 4. CONCLUSION AND OUTLOOK

The detailed measurements of properties of nuclei beyond the dripline yield important nuclear structure information for exotic nuclei far from the valley of stability. The method of sequential neutron decay spectroscopy has been applied up to $^{13}$Be. Very low energy neutron emission was observed in $^{10}$Li and $^{13}$Be. In order to confirm these transitions were to the ground-states of these nuclei and not to excited states of the daughters, total energy measurements or experiments in coincidence with $\gamma$ rays have to be performed.

Although it might be possible to extend this method towards $^{16}$B, where recently evidence for a very low-lying state was recently reported,[32] it cannot be extended to much heavier systems because of the reduced production cross sections and the increasing background. The heavier mass regions along the dripline (up to

$Z \sim 16$) can be explored by populating the nuclei of interest with single particle transfer/stripping reactions using radioactive beams. However, higher primary beam intensities are necessary in order to achieve the intensities for the secondary beam needed for these reactions.[33]

Single neutron stripping reactions with radioactive beams have already been used along the proton dripline to investigate the two-proton decay of $^{12}$O, and we used the reaction $^{9}$Be($^{12}$N,$^{11}$N) to measure the ground state of $^{11}$N. Significant strength at $E_{decay} \sim 1.2$ MeV was observed, below the presently accepted ground state with a decay energy of $E_{decay} = 1.9$ MeV. This low-lying ground state could possibly explain the large decay width of $^{12}$O and confirm the sequential decay nature of the two proton decay of $^{12}$O.

The search for di-proton emission can be extended to heavier masses, and possible candidates are $^{16}$Ne, $^{19}$Mg, $^{26}$S and $^{48}$Ni. An especially interesting experiment to search for di-proton emission was recently performed at Louvain-la-Neuve.[34] The first excited state of $^{17}$Ne is bound with respect to one proton decay but unbound with respect to two proton decay.[35] The extension of the search for ground state two proton emitters depends again on higher beam intensities, which will be available with the proposed upgrade at MSU.[33]

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