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Precise branching ratios to unbound ^{12}C states from ^{12}N and ^{12}B β-decays

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Two complementary experimental techniques have been used to extract precise branching ratios to unbound states in ^{12}C from ^{12}N and ^{12}B β-decays. In the first the three α-particles emitted after β-decay are measured in coincidence in separate detectors, while in the second method ^{12}N and ^{12}B are implanted in a detector and the summed energy of the three α-particles is measured directly. For the narrow states at 7.654 MeV (0^+) and 12.71 MeV (1^+) the resulting branching ratios are both smaller than previous measurements by a factor of $\simeq$2. The experimental results are compared to no-core shell model calculations with realistic interactions from chiral perturbation theory, and inclusion of three-nucleon forces is found to give improved agreement.

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In recent years there has been significant progress in using ab-initio methods, such as Green's function Monte Carlo (GFMC) [1] and the no-core shell-model (NCSM) [2], for the description of the low-energy structure and dynamics of light atomic nuclei. In a recent NCSM study [3] potentials from chiral perturbation theory (ChPT) were applied for the first time in the mid-p shell including three-nucleon forces (3NF). This provides a promising and long awaited bridge between nuclear structure and the underlying theory, QCD.

^{12}C is at the upper limit of the applicability of these general approaches; its ground state energy has been calculated with GFMC [1], while NCSM can also provide excited states and a range of observables [2, 3]. The existence of cluster structure in the low energy states of ^{12}C has also led to many studies using various built-in correlations; from three-alpha calculations to methods capable of combining cluster structure and shell-model like structure [4, 5]. This cluster structure makes the description of ^{12}C a particular challenge for ab-initio methods.

Gamow-Teller (GT) transitions to ^{12}C from the decays of ^{12}N and ^{12}B provide a sensitive probe of the structure of the populated states and therefore a test of these new theoretical approaches. Indeed, the shell model (jj-coupled) and cluster (SU(4) symmetry) limits predict large and vanishing GT strength to ^{12}C states respectively [6]. The strength of the inter-nucleon spin-orbit (SO) interaction is important for the mixing of these different nuclear structures. Realistic nuclear potentials with three-nucleon forces tend to have a much stronger SO interaction and one can therefore expect the GT transitions to be sensitive to this aspect. By comparing GT transitions from ^{12}N and ^{12}B the isospin asymmetry can be tested. This is a possible test for the existence of second-class currents in the weak interaction [7]. However, nuclear-structure effects probably provide the principal contribution to this asymmetry and this observable therefore also provides a sensitive test of the calculations.

At present, precise measurements exist for the GT transitions to the ground state and first 2^+ state in ^{12}C, while feeding to unbound states is known with much less precision [8]. These transitions are difficult to measure because the branching ratios are small, and the states break up into three α-particles leading to complicated decay spectra. The purpose of this Letter is to provide high precision experimental GT strengths to states in ^{12}C above the 3α break-up threshold at 7.275 MeV. We use two complementary experimental approaches to determine these branching ratios. The results are compared with state of the art NCSM calculations.

In the first approach we use the reactions ^{12}C(p,n)^{12}N and ^{11}B(d,p)^{12}B and the ISOL method to produce low energy beams of ^{12}N and ^{12}B and implant them in a thin carbon foil in the center of a large solid angle, segmented Si detector array, which permits measurement of the energy and momentum of each α-particle emitted in the decays. These measurements were carried out at the IGISOL facility of the Jyväskylä Accelerator Laboratory (JYFL) [9]. The detector array consisted of three Double Sided Silicon Strip Detectors (DSSSDs) in a horseshoe formation. Each detector has 16×16 strips on an active area of 50×50 mm^2 and a thickness of 60 μm. A Ge-detector was included in the measurements to make it possible to extract absolute branching ratios and $\log ft$ values by using the known branching ratio to the 4.44 MeV state of ^{12}C and counting the number of detected 4.44 MeV gamma-rays. The same experimental method but without the Ge-detector and only two DSSSDs has previously been used in experiments at JYFL and at CERN-ISOLDE, but never measuring both ^{12}N and ^{12}B in the same setup [10, 11].

In Fig. 1 triple-alpha spectra for the decay of ^{12}N and ^{12}B are shown. These have been constructed by adding the energy of three detected α-particles, correcting for detection efficiency, and bringing to an absolute scale using the data from the Ge-detector. Note that the detection efficiency is strongly dependent on the kinematics of the break-up. Hence decays via the ^{8}Be ground state and decays through excited states in ^{8}Be are separately corrected for detection efficiency; see [12] for details.

The second approach for measuring branching ratios is based on implanting the ^{12}N and ^{12}B nuclei in a detector. This experiment was performed at the Kernfysisch Versneller Instituut (KVI), Groningen. At this facility beams of ^{12}N and ^{12}B were produced using the same reactions as at JYFL, but in inverse kinematics. The separator of the TRIμP facility [13] filtered the beam for contaminants and defocused the beam to match the surface area of a 48×48 strip detector with an active area of 16×16 mm^2 [14, 15]. With a detector thickness of 78μm, α-particles from the decay of a nucleus implanted in the center of the detector will deposit all of their energy inside the detector. The advantage of the implantation technique is that the number of implanted ^{12}N and ^{12}B nuclei can be counted, and the triple-alpha sum energy is measured directly. It is also possible to probe the spectra at very low energies, because detector deadlayer effects are avoided. The drawback is that the information about the correlations between the emitted particles is lost when only the sum energy of the emitted α-particles is measured.

The resulting decay spectra for ^{12}N and ^{12}B are also shown in Fig. 1. In this case the ordinate is simply the fraction of implantations having a subsequent decay in the same pixel of the detector.

The absolute normalizations of the JYFL data and

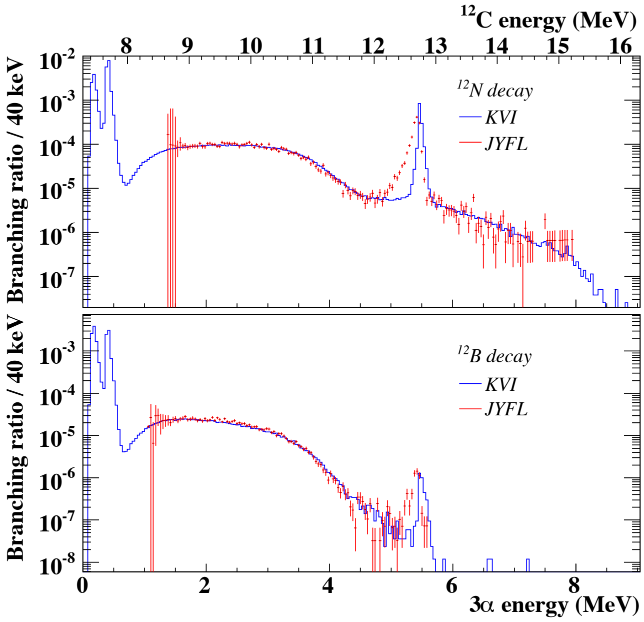

FIG. 1: Decay spectra for ^{12}N and ^{12}B from the two experiments. The branching ratio per bin, which is determined by two complementary methods in the two experiments, is shown as a function of 3α energy.

KVI data are in good agreement in the region of overlap. The KVI data extend to lower energy and include the peak corresponding to the 7.654 MeV state. The peak below this arises from energy deposition by β-particles from decays to bound states. The KVI spectra are shifted upwards by up to 50 keV compared to the JYFL spectra due to the energy deposition by β-particles. Above the 7.654 MeV peak a broad structure dominates the spectrum until the 1^+ state peak at 12.71 MeV. For ^{12}B the spectrum end point is at 13.37 MeV, while for ^{12}N another broad structure extends from the 12.71 MeV peak up to the end point at 16.3 MeV. The broad structures are the result of one or more 0^+ and 2^+ states as well as the ghost of the 7.654 MeV state [10, 11]. This is the subject of on-going analysis.

The absolute branching ratios from the JYFL and KVI experiments are shown in Table I with comparison to the literature. In several cases the literature branching ratios have been updated using the measured relative branching ratios quoted in the original papers and the latest values of quantities used for normalization; see [16] for details. The two experiments yield consistent values, but with better accuracy in the KVI experiment due to better statistics and more directly determined branching ratios. New branching ratios to the ground state can be found as one minus the sum of branching ratios to all excited states (using the literature values for the 4.44 MeV state). This has only been done using the KVI data, since the JYFL data lack information about the low energy region. For both ^{12}N- and ^{12}B-decay the branching ratios

TABLE I: Absolute branching ratios

^{12}C	^{12}N			^{12}B		
Energy (MeV)	Literature (%)	JYFL (%)	KVI (%)	Literature (%)	JYFL (%)	KVI (%)
g.s.	94.6(6)[a]	-	96.03(5)	97.2(3)[a]	-	98.03(5)
4.44	1.90(3)[a]	-	-	1.28(4)[a b]	-	-
7.65	2.7(4)[a]	-	1.41(3)	1.2(3)[c]	-	0.58(2)
9-12	0.46(15)[d]	0.44(7)	0.404(9)	0.08(2)[d]	0.058(14)	0.068(3)
12.71	0.28(8)[c]	0.108(15)	0.120(3)	-	$3.4(6)\cdot10^{-4}$	$2.8(2)\cdot10^{-4}$
12-16.3[e]	-	0.013(4)	0.020(3)	-	-	-
15.11	$3.8(8)\cdot10^{-3}$ [c]	-	$3.2(10)\cdot10^{-5}\cdot\Gamma/\Gamma_\alpha$	-	-	-
7.3-16.3	3.4(4)[a]	-	2.10(3)	1.3(3)[a]	-	0.69(2)

[a]Literature values from [8].
[b]An alternative value of 1.18(2) is given in [8].
[c]Updated as described in [16].
[d]Branching ratio to the 10.3 MeV state in [8].
[e]Excluding the 12.71 MeV peak; see the text.

for the 7.654 MeV state, coming only from the KVI experiment and omitting contributions from the ghost, are smaller than the literature values by a factor $\simeq$2. A short re-measurement at KVI confirmed that this difference is not caused by e.g. a drop of detection efficiency at the low energies of the 7.654 MeV state. Branching ratios to the broad regions in the spectra are also given in Table I. The resulting branching ratios for the 9-12 MeV region are in agreement with the literature values for the 10.3 MeV state when it is taken into account that we have excluded the contributions below 9 MeV in Table I. The branching ratios to the 12.71 MeV state have been corrected for the small gamma branch for this state, $\Gamma_\gamma/\Gamma = 0.0222(16)$ [8]. This is the first observation of this state in the decay of ^{12}B. For ^{12}N the branching ratios are a factor of $\simeq$2.5 smaller than the literature value. The branching ratio to the broad region at high energies (with the 12.71 MeV peak subtracted) has not previously been measured. The isobaric analogue state at 15.11 MeV has a small α branch, $\Gamma_\alpha/\Gamma = 0.041(9)$ [8], and is seen as a small peak in the ^{12}N decay spectrum with 29(9) counts. Assuming a negligible GT strength (B_{GT} value) to this state, the corresponding branching ratio leads to a Fermi strength of 0.6(2) inconsistent with the expected value $B_F = 2$. Accepting the theoretical Fermi strength leads to a revised value for the α width, $\Gamma_\alpha/\Gamma = 0.011(3)$, which is consistent with the value 0.012(7) in [17].

For narrow states B_{GT} values are determined from our branching ratios, BR_λ, as

$$B_{GT} = \frac{g_V^2}{g_A^2}\frac{K}{ft_{1/2;\lambda}} = \frac{g_V^2}{g_A^2}\frac{K}{ft_{1/2}}BR_\lambda \qquad (1)$$

where $K = 6147(2)$ s [18], $|g_A/g_V| = 1.2695(29)$ [19], $t_{1/2}(^{12}\mathrm{N}) = 11.000(16)$ ms [8], $t_{1/2}(^{12}\mathrm{B}) = 20.20(2)$ ms [8] and f is the standard lepton phase space factor. Values are given in Table II. For the broad regions B_{GT} values can not be found from the branching ratios in Table I, since f is energy dependent.

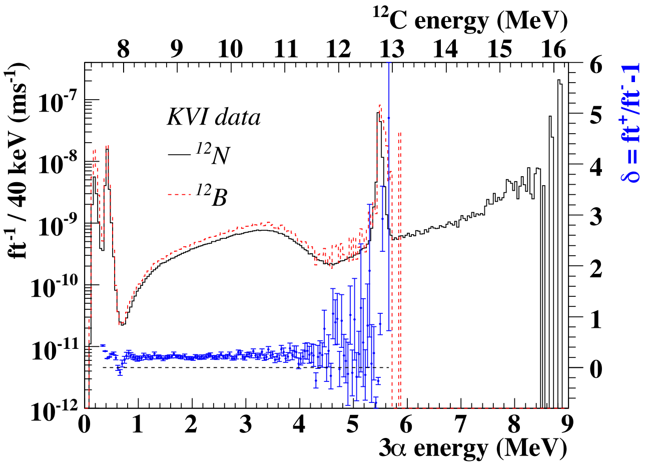

FIG. 2: Spectra of inverse ft-value per energy bin for ^{12}N and ^{12}B decays. The isospin asymmetry, δ, is also shown (points with error bars).

The isospin asymmetry is defined as $\delta = ft(\beta^+)/ft(\beta^-) - 1$ and values are given in Table II. Isospin is a good quantum number if $\delta = 0$ corresponding to equal strengths for β^+ and β^- transitions. To give the isospin asymmetry for the broad regions we plot in Fig. 2 the inverse ft-value per energy bin and calculate from that the isospin asymmetry per energy bin. We see a small constant positive shift in favor of β^--decay similar in magnitude to those in Table II. The asymmetry is seen to vary most in areas where the spectra change rapidly. These variations are mainly caused by differences in the amount of β summing due to different Q-values in the two decays. The energy independence confirms that the origin of the asymmetry is mainly nuclear structure as a second class currents explanation infers an energy dependent asymmetry [7].

TABLE II: Experimental B_{GT} values compared to NCSM results.

^{12}C	$B_{GT}(^{12}\text{N})$			$B_{GT}(^{12}\text{B})$			$\delta = \frac{B_{GT}(^{12}B)}{B_{GT}(^{12}N)} - 1$		
Energy (MeV)	Exp.	NN	NN+3NF	Exp.	NN	NN+3NF	Exp.	NN	NN+3NF
g.s.	0.2952(14)	0.081	0.337	0.331(2)	0.082	0.341	0.120(2)	0.0106	0.0128
4.44	0.0270(4)^a	0.0050	0.0054	0.0297(9)^a	0.0044	0.0044	0.10(4)^a	−0.12	−0.19
7.65	0.090(2)^b	1.18	0.851	0.108(3)^b	1.05	0.884	0.20(5)^b	−0.11	0.039
12.71	0.450(11)^c	0.710	0.662	0.49(3)^c	0.837	0.687	0.10(8)	0.178	0.0374
15-16	0.6(2)	1.50^d	0.802^d						

^{a}Literature values from [8].
^{b}The values given are for the 7.654 MeV peak only and contributions from the ghost are omitted.
^{c}Obtained by combining our experimental branching ratios.
^{d}Proposed 2_2^+ state at 15.4 MeV [8].

In Table II the experimental B_{GT} values are compared to NCSM calculations with Hamiltonians as described in [3] with and without the three-nucleon forces added. The calculations are carried out in $6\hbar\omega$ and $8\hbar\omega$ model spaces respectively. We observe a systematic improvement with experiment in calculations that include the 3NF. This is particularly striking for transitions to the ground state due to their strong sensitivity to the strength of the spin-orbit interaction that increases with the 3NF. This was already observed in earlier calculations with a different 3NF [6]. The calculated transition to the 1^+ 12.71 MeV state is in much better agreement with the present data that reduce the branching ratio by a factor of $\simeq$2.5 compared to earlier measurements. It should be noted that the current NCSM calculations do not properly describe the 7.654 MeV state. The NCSM 0_2^+ state is at about twice the excitation energy of the 7.654 MeV state and the B_{GT} values are overestimated. The alpha clustering must be taken into account to describe this state. The NCSM predicts a strong GT transition to the 2_2^+ state around 15-16 MeV with an experimental candidate at 15.4 MeV [8]. In Table II we have estimated the GT strength to the 15-16 MeV region by assuming a contribution from each bin in Fig. 2 calculated with the narrow level formula. A slightly lower value, within the quoted error, results from using the average f_β-value and the summed branching ratio for the 15-16 MeV region. The estimated 15-16 MeV GT strength matches the NCSM prediction when the 3NF is included. The isospin breaking due to the Coulomb and the strong force is included in the ChPT nucleon-nucleon interaction. Still, the calculated asymmetries are underestimated as no coupling to the continuum is included and the employed ChPT 3NF is isospin invariant.

In conclusion refinements in both experiment and theory leads to a satisfactory ab-initio understanding of non-cluster states in ^{12}C.

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