Observation of a new transition in the β-delayed neutron decay of ^{16}C

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(Received 3 October 2000; published 14 February 2001)

A new transition is reported in the β-delayed neutron decay of ^{16}C. The energy of the associated neutrons is 3.29 ± 0.03 MeV, leading to the feeding, with a branching ratio of $\sim1\%$, of a probable 1^+ level in ^{16}N at 6.00 ± 0.03 MeV. Such an observation is in good accordance with shell model calculations carried out within the $0p1s0d$ model space.

DOI: 10.1103/PhysRevC.63.037302 PACS number(s): 27.20.+n, 21.10.Pc, 21.60.Cs

As part of a program to investigate light neutron-rich nuclei via β-delayed neutron decay, measurements of the decay of the delayed neutron emitters ^{15}B, ^{16}C, and ^{17}N have been undertaken using the new TONNERRE (TONneau pour NEutrons REtardés) array [1]. In this Brief Report some of these results are presented with particular attention focused on the decay of ^{16}C where a new transition has been observed.

The β-delayed neutron decay of ^{16}C has been studied previously by Alburger *et al.* [2] together with that of ^{17}N using ^{3}He counters. Two neutron lines were reported for ^{16}C with energies of 0.79 ± 0.03 and 1.72 ± 0.05 MeV and relative intensities of $I_{0.79}/I_{1.72}=5.4\pm0.7$.

In the measurement of delayed neutrons it is important to have available reference points for energy calibration and, moreover, to determine the intrinsic detection efficiency. The latter is crucial for deducing the branching ratios for the different transitions. Typically, well-established β-*n* emitters such as ^{16}C and ^{17}N are used. Recent studies [3,4], however, employing the decay of ^{16}C as a reference, have not reported the observation of any neutrons with energies beyond 1.71 MeV.

The setup used in the present experiment together with the analysis procedures are described in detail in Ref. [1]. ^{15}B, ^{16}C, and ^{17}N beams were produced at GANIL by projectile fragmentation of a 77 MeV/nucleon ^{18}O primary beam on a 4-mm Be target. The ions of interest were selected by the double achromatic LISE3 spectrometer [5] where a degrader of Be (average thickness of 1000 μm) was mounted in the intermediate focal plane between the two dipole magnets. At the end of LISE3, the beams were focused onto a detector telescope and stopped in an implantation detector, a $3\times3\times1$ cm^3 NE102 plastic scintillator block viewed by two photomultiplier tubes (PMTs). The telescope consisted of an Al degrader, in order to stop the ions at the center of the plastic, placed in the middle of two thin Si detectors (300 μm and XY 300 μm) for the beam monitoring. The energy loss in the Si detectors in combination with the time of flight in the spectrometer allowed an event-by-event identification. Behind the plastic, a 500-μm Si detector was used as a veto. The target was surrounded by the TONNERRE array consisting of 32 elements, each comprising a 160-cm-long scintillator bar (BC400), 20 cm wide and 4 cm thickness. The radius of curvature and neutron flight path is 120 cm. Each element is viewed by two PMTs; the requirement of an event registered in both significantly reduces the contribution due to noise, while the time difference provides for a determination of the position of the event along the detector. The neutron detector array covered a solid angle of 45% of 4π.

The decay of ^{15}B, ^{16}C, and ^{17}N produces neutrons [12] with energies of 1.76, 2.81, 3.23, 4.32, and 4.75 MeV (^{15}B); 0.81 and 1.71 MeV (^{16}C); and 0.38, 1.16, and 1.69 MeV (^{17}N). Typical neutron time-of-flight (TOF) and energy spectra obtained using the TONNERRE array are shown in Fig. 1 for the decay of ^{17}N. The intrinsic neutron efficiency, deduced from the observed intensities and the known branching ratios, is displayed in Fig. 2 and is in agreement with preliminary tests made with a Cf source [1]. The intrinsic efficiency is rather high between 1 and 5 MeV and as such allows for the detection of very weak transitions. The presence in the energy spectra for the decay of ^{17}N of the 0.38 MeV neutron line demonstrates that the array can be operated at rather low threshold (~300 keV), a significant feature for a detector of such dimension.

We now turn to the measurements made for the decay of ^{16}C where, as may be seen in the TOF spectrum (Fig. 3), the two well-known neutron lines at 0.81 and 1.71 MeV (98 and 67.4 ns, respectively) are present along with a third line at lower TOF (48.6 ± 0.2 ns). The latter peak is present in the data obtained with each individual module and with all possible selections that may be applied to the data [1]. The corresponding energy is 3.29 ± 0.03 MeV and the branching ratio $1.0\pm0.2\%$. The β-time spectrum for ^{16}C yields a period of 753 ± 8 ms, which agrees very well with the known value of 747 ± 8 ms [6]. The time spectra obtained in coincidence with the neutron lines at 0.81, 1.71, and 3.29 MeV are given in Fig. 4 and yield periods of 770 ± 35, 780 ± 45, and 700 ± 70 ms, respectively.

The event-by-event registration of the implanted ions allowed checks to be made for contributions arising from any contaminants in the beam. The purity of the ^{16}C beam was estimated to be better than 10^{-6}. In addition, simulations made with the LISE code [7] for the production rates of the various ions produced in the fragmentation process suggest that the only possible contaminants would have been ^{14}B and ^{18}N. The corresponding counting rates, however, are incompatible with the observed intensity of the 3.29-MeV neutron

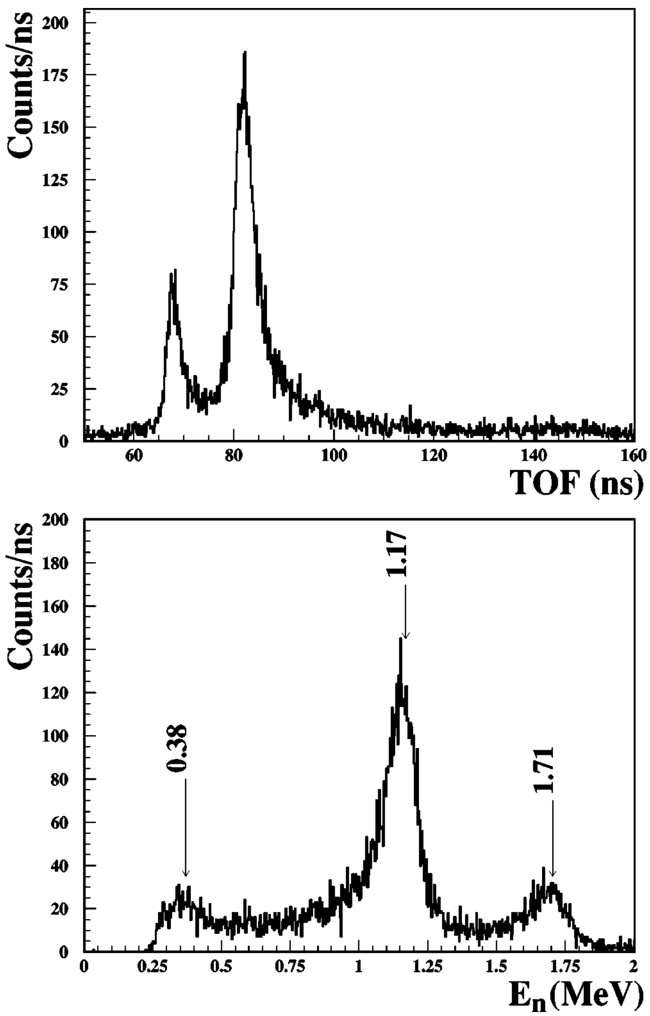

FIG. 1. Neutron TOF and energy spectra for the decay of ^{17}N.

line. Moreover, the ^{14}B half-life of 13.8 ms definitively excludes such a possibility. The case of ^{18}N is more complicated since the half-life is 624 ms, relatively close to that of ^{16}C (747 ms). In particular, ^{18}N is a known β-*n* emitter with a neutron line at 3.26 ± 0.03 MeV and a branching ratio of $0.19\pm0.04\,\%$ [3]. There are, however, a number of other lines known at lower energies, with the most intense (branching ratio of $0.43\pm0.03\,\%$) at 2.46 ± 0.03 MeV. It is clear from our data that we have no neutron line between 2 and 3 MeV (corresponding to a TOF between 62 and 51 ns). Gamma rays were also measured in coincidence with the β decay using two large volume (120 %) Ge detectors. No gamma rays were registered in coincidence with the neutrons of 0.81, 1.71, and 3.29 MeV. This observation indicates that the 3.29-MeV neutron line should be assigned to a β-decay feeding directly a level at 6.00 ± 0.03 MeV in ^{16}N. The measured branching ratio of $1.0\pm0.2\,\%$ together with the energy permits, using the Wilkinson parametrization [8], a $\log(ft)$ value of 3.86 ± 0.10 to be deduced. This value is very close to those associated with the 1.71- and 0.81-MeV transitions—$\log(ft)$ values of 3.55 and 3.82, respectively—thus indicating that the present transition is allowed and that the level feed in ^{16}N is most probably 1^+.

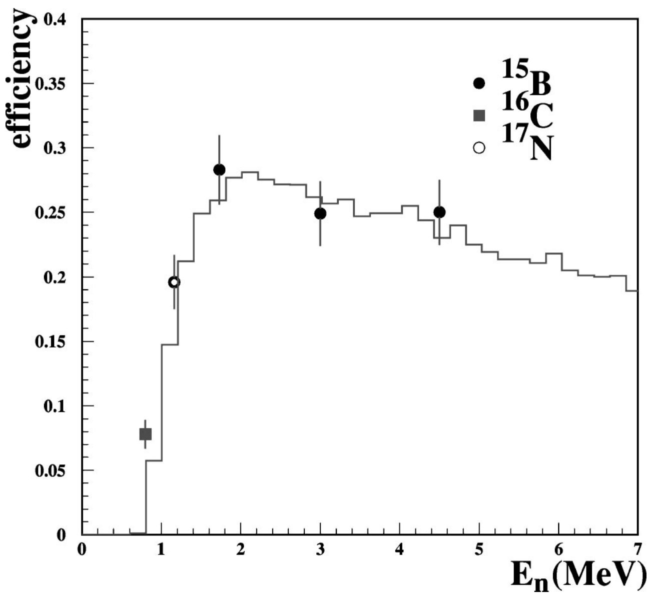

FIG. 2. The experimentally measured intrinsic neutron detection efficiency of TONNERRE (points) and the result of a Monte Carlo simulation [1] assuming a threshold of 100 keV ee^-.

As noted earlier, experimental information on the β-delayed neutron decay of ^{16}C has previously been obtained by Alburger *et al.* [2]. Two transitions were reported feeding states at 3.353 and 4.32 MeV in ^{16}N with $\log(ft)$ values of 3.55 and 3.83 corresponding, for pure Gamow-Teller decays, to $B(\mathrm{GT})$ values of 1.73 ± 0.04 and 0.92 ± 0.10, respectively. As this study employed ^{3}He counters with quite low efficiency at high energies, transitions at energies above ~2 MeV with branching ratios of less than 2.0% could not be observed [9].

At the time of these measurements, it had been demonstrated that the Millener-Kurath (MK) interaction fails to reproduce the observed Gamow-Teller transitions to the 1^+ states at 3.353 and 4.32 MeV. As noted in Ref. [2], Millener predicted three 1^+ states to which β decay is strong, with

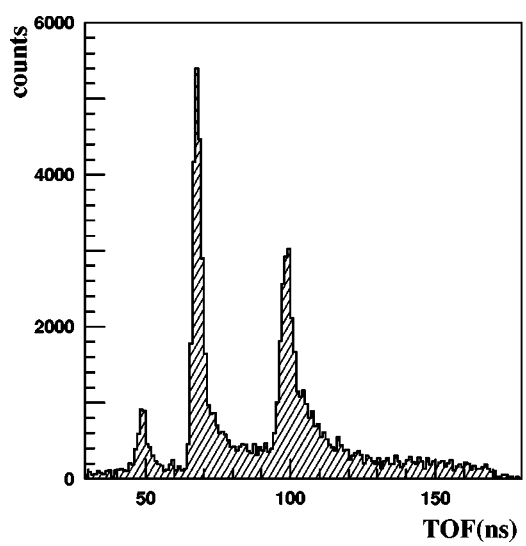

FIG. 3. β-delayed neutron TOF spectrum for the decay of ^{16}C.

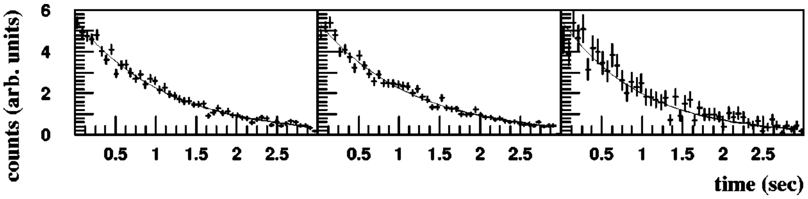

FIG. 4. β-particle time spectra for the decay of ^{16}C in coincidence (from left to right) with the neutron lines at 0.8, 1.7, and 3.3 MeV.

$\log(ft)$ values in the range 3.2–3.8. These states, however, were predicted at much higher excitation energy (>6.0 MeV) with $B(\mathrm{GT})$ values of 0.002 and 1.413 derived for the two observed branches, whereas Snover *et al.*, using somewhat different parameters, found values of 0.002 and 0.567, respectively [10]. Both of these approaches used the MK interaction and a GT operator appropriate for free nucleons.

More recently Warburton and Brown [9] have calculated the GT decay of ^{16}C using three different effective interactions (PSDP, PSDT, and WBT) within the $0p1s0d$ shell model space. These calculations reproduced quite well the two first 1^+ states with excitation energies around 2.3–2.8 and 3.3–3.6 MeV, and B(GT) values of 0.8–1.3 and 0.3–0.6, respectively. Warburton and Brown attribute this success mainly to the fact that the cross-shell potential is more complex than in the MK approach with more quantitatively determined parameters and thus more accurate wave functions. In a similar comparison, Chou *et al.* [11] have demonstrated that for the decay of ^{16}C to $^{16}\mathrm{N}(1_1^+)$ a large difference occurs between the WBT and MK3 calculations, with the WBT interaction providing rather good agreement with the experimental results. The difference appeared to be a complex function of both the $0p$-shell and cross-shell interactions but the authors were not able to postulate a simple explanation for it.

More interesting are the predictions of possible β decays feeding higher-lying 1^+ levels in ^{16}N. Warburton and Brown predict a group of three levels with energies between 5.5 and 7.0 MeV. The two highest were reasonably assigned to the known 1^+ levels at 6.505 and 7.02 MeV [12]. The lowest could not be unambiguously identified and it was assumed that it was the analog of the third 1^+ state identified at 18.79 MeV in ^{16}O [13] and therefore should have an energy of 5.894 MeV in ^{16}N. The calculated $B(\mathrm{GT})$ for this level varies for the three interactions from 0.56 to 1.07. The experimental results together with all the theoretical predictions are summarized in Table I.

It is clear that the transition reported here to a level located at 6.00 ± 0.03 MeV in ^{16}N with a $\log(ft)$ of 3.86 ±0.01 [corresponding to a $B(\mathrm{GT})$ for a pure Gamow-Teller transition of 0.85 ± 0.18] is in line with the above predictions (Table I). Experimentally, there is no contradiction with the work of Alburger *et al.* [2], which, due to the branching ratio limit of 2.0%, were unable to detect such a low-intensity transition.

Following the WBT calculations which Warburton and Brown consider as superior compared to those using the PSDP and PSDT interactions, two other neutron lines with energies around 3.8 and 4.2 MeV may be expected. The corresponding branching ratios are $\sim0.2\%$ and $\sim0.0025\%$, respectively. It is clear that we are not able to observe such a weak transition as the 4.2-MeV line. A careful study of our data in the region of 3.8 MeV (TOF of 45.46 ns) did not reveal any such transition. Given an experimental branching ratio limit of 0.1% (the efficiency is nearly constant between 3 and 5 MeV) for both transitions, limits of 0.3 and 1.6 may be set on the $B(\mathrm{GT})$ (Table I) for transitions to the levels at 6.505 and 7.02 MeV.

A new transition with an energy of 3.29 ± 0.03 MeV has been observed in the β-delayed neutron decay of ^{16}C. This transition feeds directly [$\log(ft)=3.86\pm0.18$] a 1^+ level in ^{16}N at 6.00 ± 0.03 MeV. These results are well understood within the framework of shell model calculations carried out within the $0p1s0d$ model space.

We would like to thank the staff of the LPC for their involvement in the construction and operation of the TONNERRE array. We are also grateful to the assistance provided by the technical staff of GANIL during the experiment.

TABLE I. Comparison of predicted (MK, PSDS, PSDT, WBT) and experimental (Expt.) excitation energies and $B(\mathrm{GT})$ values for the decay in ^{16}C to the $k=1$–5 (1_k^+) states of ^{16}N. The results of the present measurement are noted in italics.

	E_x (keV)					B(GT)				
k	Expt.	MK[a]	PSDP[b]	PSDT[b]	WBT[b]	Expt.	MK[a]	PSDP[b]	PSDT[b]	WBT[b]
1	3353	>6000	2858	2881	2835	1.728	0.002	0.813	1.231	1.316
2	4320	>6000	3325	3612	3470	0.917	1.413	0.621	0.415	0.321
3	*6000(30)*	>6000	5559	5638	5474	*0.85(18)*	-	1.053	1.069	0.560
4	(6505)[c]	-	6317	6443	6136	*<0.3*	-	0.020	0.01	0.541
5	(7020)[c]	-	6884	6997	6273	*<1.6*	-	1.352	1.550	0.409

[a]From Ref. [2].
[b]From Ref. [9].
[c]Suggested assignment [12].

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