Observation of a new transition in the β-delayed neutron decay of ^{18}N

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A new transition is reported in the beta-delayed neutron decay of ^{18}N. The observed neutron energy is 3.78±0.05 MeV with a branching ratio of 0.05±0.03%, which corresponds to an excitation energy of 12.05±0.05 MeV in the daughter nucleus ^{18}O. The log *ft* value of this transition is 5.24±0.3, which, together with the previously reported electron scattering data, determines the J^{π} value of this level to be 1^-. The experimental data are compared to the shell model calculations in different model spaces.

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β-delayed neutron emission is often the dominant decay mode for light neutron-rich nuclei. The large decay energy (Q value) allows us to populate the highly excited states of the daughter nucleus, which are of special importance to study the nuclear structure of the unstable nuclei. So far many experiments of this kind have been carried out in several laboratories for nucleus such as ^{17,18,19,20}N [1–4], ^{16,17,18,19,22}C [5–8], ^{15,17,19}B [9–11], and ^{12,14}Be [12,13].

For ^{18}N [14–21] in particular the β-decay was initially studied by Chase *et al.* in 1964. The attempt to measure the energy spectrum of the delayed neutrons was first made by Scheller *et al.* [2], and nine neutron peaks were observed at energies from 0.99 to 3.26 MeV with a total branching ratio of 2.2±0.4%. However this only accounts for a small portion of the total neutron-emission branching ratio (Pn) of 14.3±2.0% determined by Reeder *et al.* [16]. The missing probability is attributed to the relatively high neutron detection threshold and the poor statistics in that experiment. We have recently reported some new results for the beta-delayed neutron emission of ^{18}N [1]. In the experiment special effort was made to reduce the energy threshold for neutron detection. In addition to the previously used neutron sphere [22], which has an advantage of covering a large solid angle but a disadvantage of having a high neutron energy threshold, a neutron wall composed of short (40.0 cm × 4.5 cm × 2.5 cm) scintillation bars was used for detecting low energies neutrons. Two low-energy neutron groups at 0.58±0.02 MeV and 0.79±0.04 MeV and with branching ratios of 5.14±1.12% and 0.28±0.06%, respectively, were observed by the neutron wall [1].

In this Brief Report we present some additional results obtained by the neutron sphere which is in favor of detecting the high energy part of the emitted neutrons. A new transition in the beta-delayed neutron decay of ^{18}N was observed and is compared to the shell model calculation.

The detailed description of the experimental setup was given in Ref. [1]. The primary beam composed of ^{22}Ne ions at 68.8 MeV/nucleon was provided by the HIRFL in Lanzhou and impinged on a ^{9}Be primary target. The produced fragments were separated, purified, and collected using Radioactive Ion Beam Line in Lanzhou (RIBLL) [23]. The secondary beam composed of mostly ^{18}N passed through a thin aluminum window and stopped in an implantation detector (NE102, 3.0 mm thick) which was placed at the center of the neutron sphere. An energy degrader and a silicon surface-barrier (dE) detector of 325 um thickness were installed upstream of the implantation detector in order to define the required beam energy and to monitor the purity of the ^{18}N beam (about 95%), respectively. The dE detector also allowed us to count the number of ^{18}N ions deposited in the implantation detector. Another Si detector was placed downstream of the implantation detector in order to veto the ^{18}N ions which were eventually passed through the implantation detector. The neutron sphere was composed of eight identical plastic scintillation counters (BC408) [22]. Each counter has a length of 157 cm and curved to a radius of 100 cm in order to have the same flight path length for neutrons emitted from the implantation detector. The thickness of each scintillator is 2.5 cm, and the width is 40 cm at the middle of the plate and reduced to 20 cm at both ends. Both ends are read by EMI-9214B photomultiplier tube via the light guide of 30 cm long.

The mean time taken from both ends of the implantation detector was served as the starting signal for the time-of-flight (TOF) measurement of the emitted neutrons whereas the stop signals were provided by the scintillation counters of the sphere. The TOF spectra, as shown in Fig. 1, were calibrated using an electronic time calibrator and the zero point was determined from the position of a prompt peak corresponding to relativistic electrons. The calibration was also verified by the time-of-flight of two groups of neutrons from the known decay of ^{17}N in a calibration run at the beginning of the same experiment.

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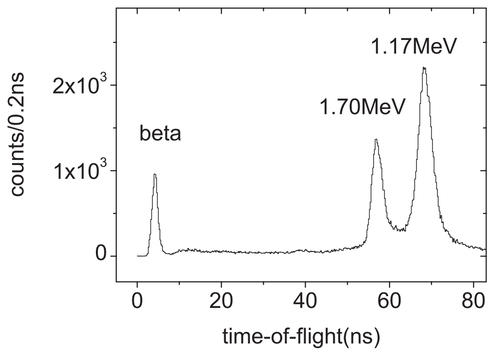

FIG. 1. Neutron time-of-flight spectrum from the decay of ^{17}N detected by the neutron sphere.

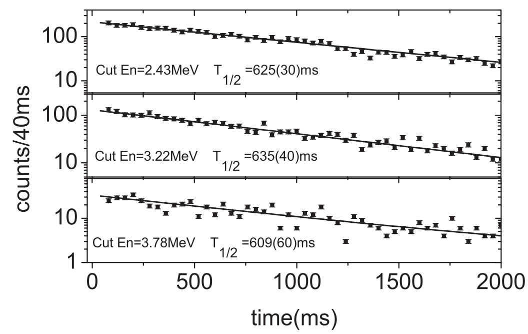

FIG. 3. β decay time spectra for ^{18}N gated by neutron peaks at 2.43, 3.22, and 3.78 MeV, as described in the text.

The neutron time-of-flight spectrum from ^{18}N was measured by the neutron sphere (Fig. 2). Nine neutron peaks were obtained by fitting the spectrum with Gaussian peak functions plus a cubic polynomial background function, using the widely adopted program PEAKFITS. The corresponding neutron energies in the laboratory are $E_n(\text{lab}) = 3.78\pm0.05$, 3.22 ± 0.04, 2.76 ± 0.04, 2.43 ± 0.04, 2.05 ± 0.03, 1.79 ± 0.03, 1.58 ± 0.03, 1.35 ± 0.03, and 1.13 ± 0.03 MeV. Compared with the previously published results obtained from the data taken by the neutron wall [1], one more peak at 3.78 MeV is identified which stands well above the background. An attempt was made to fit the spectrum without this high energy peak but it is impossible to reproduce the spectrum shape at the high energy side. Apart from this 3.78 MeV peak, the positions and widths of other eight neutron peaks are in agreement with those measured by the neutron walls as shown in Fig. 4 of Ref. [1]. In contrast the relative number of counts as a function of neutron energy is quite different for the neutron sphere than for the neutron wall, corresponding to the the different detecting efficiency as a function of neutron energy for these two detector systems. For the current measurement with the neutron sphere the peaks below 2.05 MeV have low statistics and are identified in the fitting procedure by initiating the peak positions according to the previous measurements [1,2] which have much higher statistics in this low energy region. The large solid angle (3.75% of 4π sr per one unit of the neutron sphere) and the relatively low background counting are the main reasons for which we were able to observe the high energy peak at 3.78 MeV by the neutron sphere but not by the neutron wall. After accounting for the recoil energy of the emitter and converting neutron energy to the center-of-mass system, the excited states in ^{18}O populated by the beta-decays of ^{18}N were obtained and listed in Table I.

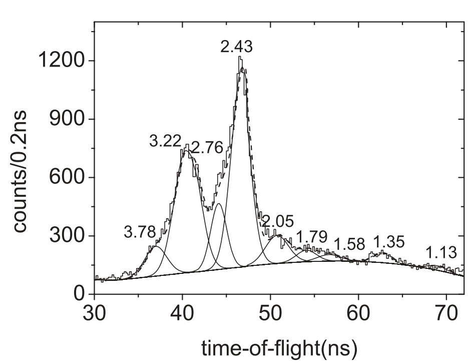

FIG. 2. Neutron time-of-flight spectrum from the decay of ^{18}N detected by the neutron sphere. The data are fitted with Gaussian peak functions plus a cubic polynomial background function. The neutron energy (in MeV) for each peak is indicated by the number at the top of each peak. The step vert solid, straight dotted, and straight solid lines stand for original data, fitted data, and fitted neutron peaks, respectively.

The β decay half-life for ^{18}N was checked by gating the β time spectrum corresponding to various neutron peaks. Figure 3 shows three examples for neutron peaks around 2.43, 3.22, and 3.78 MeV. For 2.43 and 3.22 MeV neutron groups the gates were chosen as the full width at 2/3 of the maximum, whereas for the 3.78 MeV neutron group the gate was chosen as the left half of the peak. The half-lives of 625 ± 30 ms, 635 ± 40 ms, and 609 ± 60 ms, respectively, were obtained which are all in good agreement with the previously reported value of 624 ± 12 ms. This provides a good proof that the origin of the emitted neutrons is ^{18}N. The major impurity contents of the beam is some 5% ^{20}O, which has a β decay half-life of 13.51 s, much larger than what observed. Therefore its contamination to the coincident measurement of the present experiment is negligible.

In order to determine the absolute branching ratio (BR) of the newly observed neutron group at 3.78 MeV, it is necessary to know the detection efficiency at this energy for the neutron sphere. It should be noted that the efficiency changes according to the assembly condition and therefore the online calibration for each experiment is required. For the present experiment the online calibration using ^{17}N beam can only provide the efficiency up to 1.73 MeV as shown in Fig. 1. We thus decide to use the results obtained by the neutron wall for ^{18}N in the same experiment. The efficiency for the neutron wall has been determined up to 3.22 MeV [1]. By comparing the number of neutrons in each neutron peak measured by the neutron sphere to that generated from the β decay of the ^{18}N according to the known BR, the efficiency curve of the neutron sphere as a function of neutron energy can be obtained for energies from 1.13 to 3.22 MeV. Two groups of β-delayed neutrons from ^{17}N could be used to verify the low energy part of this efficiency distribution. It is found that the efficiency curve goes upward at energies from about 1 MeV to 2 MeV but then keeps almost constant for neutron

TABLE I. Neutron energies and excitation levels in ^{18}O, obtained from the present experiment, compared with the previously published experimental data [21] of allowed β decay and theoretical predictions given in Ref. [25].

E_n(MeV)	E_x(MeV) and J^π	From Ref. [21]	From Ref. [25]
1.13±0.03	9.24±0.03 (0-2)$^-$	9.27±0.02	
		9.414±0.02	
1.35±0.03	9.47±0.03 (0-2)$^-$	9.48±0.02	9.545 2$^-$
1.58±0.04	9.58±0.04 (0-2)$^-$	9.672±0.01 3$^-$	
		9.713±0.01 5$^-$	
1.79±0.04	9.87±0.04 (0-2)$^-$	9.890±0.01	10.081 2$^-$
		10.118±0.01 3$^-$	10.196 1$^-$
2.05±0.04	10.14±0.04 (0-2)$^-$	10.24±0.02 (0-2)$^-$	10.251 1$^-$
		10.396±0.01 (3)$^-$	
		10.43±0.04 (2$^-$)	
2.43±0.04	10.62±0.04 (0-2)$^-$	10.595±0.02	
		10.67±0.02 2$^-$	
		10.82±0.02	
		10.91±0.02	10.942 2$^-$
2.76±0.04	10.97±0.04 (0-2)$^-$	10.99±0.02 2$^-$	10.951 1$^-$
		11.06 6$^-$	
		11.13±0.02	11.11 1$^-$
3.22 ±0.04	11.45±0.04 (0-2)$^-$	11.49±0.03 (0-2)$^-$	11.34 2$^-$
		11.52±0.05 2$^-$	
		11.62±0.02 5$^-$	
		11.67±0.02 3$^-$	
		11.82±0.02 3$^-$	
		11.90±0.03 2$^-$	
3.78±0.05	12.05±0.05 (0-2)$^-$	12.09±0.02 1$^-$ or 2$^+$	11.814 1$^-$
		12.25±0.02	12.209 2$^-$

energies above 2 MeV up to 3.2 MeV. We thus extrapolate this constant efficiency to 3.78 MeV. This is reasonable since for normal neutron detection systems the efficiency always changes very slowly with energy after it attains the maximum value [22]. Then based on the ratio of the number of counts in the neutron peak at 3.78 MeV to that at 3.22 MeV, the BR of the 3.78 MeV neutron group can be determined to be 0.05±0.03%. The relatively large error includes not only the statistical uncertainty but also the uncertainty of the efficiency determination which is about 20%. The log*ft* values can then be calculated from the half-life of ^{18}N and the branching ratios, and the Gamow-Teller decay strengths [B(GT)] from the function $B(\mathrm{GT}) = 6145/ft_{1/2}$. These values for 3.78 MeV neutron group are 5.24±0.30 and 0.036±0.022, respectively, which suggest that this decay is an allowed transitions with the spin-parity of the final state in ^{18}O to be $J^\pi = (0\text{–}2)^-$.

The excitation energies and J^π values for ^{18}O obtained from our experiment are listed in Table I together with a compilation of previously observed levels given in Ref. [21] and the theoretical calculations given in Ref. [25]. A state at about 12.09±0.02 MeV (corresponding to neutron energy at 3.78±0.05 MeV) was indeed observed by Seller *et al.* from an electron scattering experiment ^{18}O$(e, e')^{18}$O [24]. They find that the spin-parity of this level is 1$^-$ or 2$^+$. The overlap of our results with Seller's results determines a J^π value of this newly observed state to be 1$^-$.

Since the beta decay energy of ^{18}N is 13.899 MeV and the neutron emission threshold is $S_n = 8.044$ MeV, β delayed neutrons with energies below 5.5 MeV should all be possible from the energy point of view. However no neutron peaks between 3.78 and 5.5 MeV were observed within the limit of the detection background. We then estimated that for ^{18}O the 3.78 MeV neutron peak was indeed the highest energy one with an observable probability.

The shell-model calculation was carried out using the code OXBASH in the *psd* and *spsdpf* model spaces. The WBT

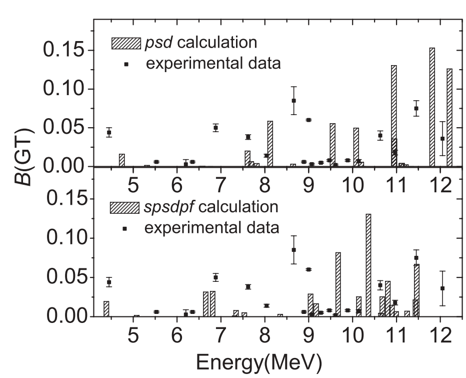

FIG. 4. Comparison of shell model calculation of B(GT) values for all the allowed beta-decay of ^{18}N to neutron unbound states, α unbound states, and γ bound states of ^{18}O.

TABLE II. The comparison of experimental and theoretical excitation energies of ^{18}O nucleus for B(GT) values larger than 0.015.

Experiment		*psd* caculation	
E_x(MeV)	B(GT)	E_x(MeV)	B(GT)
4.45 ± 0.0001[a]	0.044 ± 0.006[b]	4.741	0.016
6.88 ± 0.0003[a]	0.050 ± 0.005[a]	7.606	0.020
7.62 ± 0.0007[a]	0.038 ± 0.003[b]	8.121	0.059
8.66 ± 0.03[c]	0.083 ± 0.018[c]	9.545	0.055
(9.00 ± 0.2)[a]	0.060[b]	10.081	0.050
10.62 ± 0.04[c]	0.047 ± 0.006[c]	10.942	0.130
10.97 ± 0.04[c]	0.018 ± 0.003[c]	10.951	0.036
11.45 ± 0.04[c]	0.075 ± 0.010[c]	11.814	0.153
12.05 ± 0.05[c]	0.036 ± 0.022[c]	12.209	0.126

[a]From Ref. [18].
[b]From Ref. [21].
[c]From our experiment.

interaction was used, and only the allowed β decay was considered. The detailed discussion about the calculation was given in Ref. [25]. The levels calculated in *psd* model space are listed in Table I in comparison to our experimental data. For the first time, Fig. 4 shows experimental B(GT) values of all the allowed β-decay from ^{18}N to the neutron unbound states [1], α unbound states [18] and γ bound states [21] of ^{18}O together with the theoretical calculations in *psd* and *spsdpf* model spaces, respectively. It can be seen that the B(GT) distribution obtained from the present experiment and previous experiment is qualitatively in agreement with that calculated in *psd* model space. But if we looked at all the levels with relatively large B(GT) values (>0.015) as shown in Fig. 4 and listed in Table II, the calculated energies seem systematically to exceed those of the measured ones, as also indicated by the authors of Ref. [25]. This might shed light on the future improvement of the theoretical models. Strong B(GT) values are not predicted around 12.05 MeV in the *spsdpf* calculations, but are predicted in the *psd* calculations. Some strong B(GT) strengths between 9.5 and 12.0 MeV are predicted in *spsdpf* calculations, which was not seen, not only in our experiment but also in Scheller's experiment [2]. The summed Gamow-Teller strength of allowed β decay to these predicted $(0–2)^-$ states between 4.456 to 12.05 MeV in ^{18}O is $B(\mathrm{GT}) = 0.576$ in *psd* space or $B(\mathrm{GT}) = 0.675$ in *spsdpf* space as compared to the total deduced $B(\mathrm{GT}) = 0.514 \pm 0.092$ for the experimental data. We thus consider that the *psd* calculation gives better agreement with the experimental data than that with the *fp*-shell involved, indicating that the observed levels of ^{18}O are mainly produced by one particle excitation from the *p*-shell to the *sd*-shell.

In summary a new transition with an energy of 3.78 ± 0.05 MeV and a small branching ratio of $0.05 \pm 0.03\%$ was observed in the beta-delayed neutron decay of ^{18}N. This transition feeds an excitation level of ^{18}O at 12.09 MeV. The $\log ft$ value of this transition is 5.24 ± 0.3, which, together with the previously reported electron scattering data, allows us to determine the J^π value of this level to be 1^-. The experimental results are compared to the OXBASH calculation using *psd* or *spsdpf* model space and applying WBT interaction. The calculation with *psd* space qualitatively reproduces the experimental data. The lack of quantitative agreement between the theoretical predictions and the measurements suggests further development of the appropriate structure model.

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