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β-delayed α decay of ^{17}N

M. Dombsky,[1,2] L. Buchmann,[3] J. M. D'Auria,[1] U. Giesen,[3,4] K. P. Jackson,[3] J. D. King,[4]
E. Korkmaz,[2] R. G. Korteling,[1] P. McNeely,[2] J. Powell,[4] G. Roy,[2] M. Trinczek,[1] and J. Vincent[3]
[1] *Simon Fraser University, Burnaby, British Columbia, Canada V5A 1S6*
[2] *University of Alberta, Edmonton, Alberta, Canada T6G 2J1*
[3] *TRIUMF, Vancouver, British Columbia, Canada V6T 2A3*
[4] *University of Toronto, Toronto, Ontario, Canada M5S 1A7*
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The β-delayed α spectrum of ^{17}N has been measured using a molecular ^{17}NO$^+$ beam from the TRIUMF isotope separator. Thin surface barrier detector pairs were used to count the α particles in coincidence with ^{13}C recoil nuclei. The resulting spectrum has been fitted with a K-matrix parametrization. The β-delayed α decay of states at 7.99 and 8.20 MeV in the ^{17}O daughter has been observed. A total $\beta\alpha$-branching ratio of $(2.5 \pm 0.4) \times 10^{-5}$ has been determined for this decay mode of ^{17}N.

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I. INTRODUCTION

In a recent study in our laboratory, the $E1$ component of the astrophysical S factor for the ^{12}C$(\alpha,\gamma)^{16}$O reaction was deduced, in part, from a precision measurement of the β-delayed α spectrum of ^{16}N [1]. In order to identify contaminant contributions to the α spectrum from nitrogen nuclides other than ^{16}N, the β-delayed α spectra of ^{17}N and ^{18}N were also measured.

Although both ^{16}N and ^{18}N are known β-delayed α emitters, this form of decay has previously not been observed for ^{17}N. However, with a Q_β of 8.680 MeV for ^{17}N and an α separation energy of 6.359 MeV in ^{17}O, the β-delayed α emission of ^{17}N is allowed by 2.321 MeV. Approximately 95% of ^{17}N β decay is accounted for by β-delayed neutron emission from states at 4.55, 5.38, and 5.94 MeV excitation in the ^{17}O daughter (see Fig. 1). The remainder of the β decay populates mainly the ground and the first two excited states of ^{17}O (below the neutron emission threshold) [2]. Using a high-efficiency surface-barrier detector system, designed to measure β-delayed charged particle emission [1,3], low-intensity, β-delayed α branches have been observed, for the first time, from states at 7.99 and 8.20 MeV in ^{17}O.

II. EXPERIMENTAL DETAILS

A radioactive ion beam of ^{17}N was produced using the thick-target on-line isotope separator, TISOL, at the TRIUMF cyclotron facility [4,5]. A 13 g/cm^2 target of Zeolite X spheres contained in a stainless steel target oven was irradiated with a 500 MeV, 1.5 μA proton beam. The target was heated to about 600 °C and was coupled to the electron cyclotron resonance (ECR) ion source [6]. Using an extraction voltage of 12 kV, ion beams were magnetically mass analyzed and transported to a low-background experimental area where they were implanted into thin (10 μg/cm^2) self-supporting collector carbon foils.

Four 1-cm-diam collector foils were positioned (with 90° relative spacing) about the circumference of a wheel rotating in the plane perpendicular to the ion beam axis. The wheel was mounted such that one foil intercepted the ion beam while the other three were simultaneously positioned between three pairs of silicon surface-barrier detectors. Successive 90° rotations of the wheel allowed collection of the ion beam and simultaneous counting of previously implanted foils at the three detector stations.

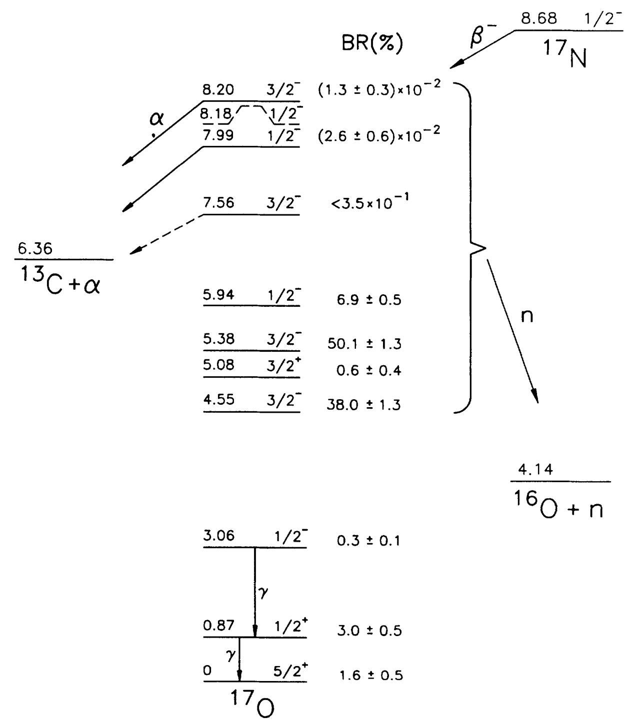

FIG. 1. β-decay scheme of ^{17}N. Level energies are given in MeV above the ground state of ^{17}O. Branching ratios to states below 7 MeV are from Ref. [2].

The 90° rotation time was measured to be 0.2 s, while a collect/count dwell time of 4 s was used to optimize the collecting and counting efficiency and suppress contaminant activities having different half-lives. With the foils positioned between the detectors ($\sim$ 8 mm separation), alpha particles were collected in coincidence with recoil carbon nuclei in the opposite detector.

Thin (10.6–15.8 μm) transmission-mount Si surface-barrier detectors, with 50 mm^2 active areas, were used to minimize the deposited energy of the more intense β activity. An 8-mm-diam, liquid-nitrogen-cooled collimator was mounted immediately upstream of the collector foil to ensure centering of the implanted ion beam and to avoid carbon deposition on the foil. Detector signals were processed and written to tape in an event-by-event mode for subsequent off-line analysis. A trigger condition was set such that all analog-to-digital converter (ADC) outputs were recorded whenever at least one detector registered an event corresponding to an α-particle energy greater than about 250 keV. Each event was tagged with its time, relative to the end of each wheel rotation, for determining half-life information. To avoid electronic noise, data acquisition was disabled during wheel rotation and coincidence events from unpaired detectors were discarded.

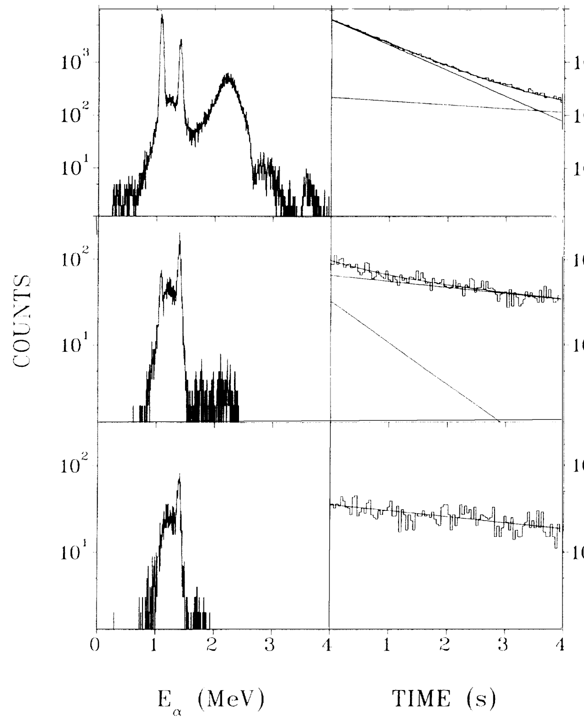

FIG. 2. Delayed α spectra from the three detector stations as functions of energy and time. The first spectrum is predominantly ^{18}N, while the last is entirely due to ^{17}N.

III. β-DELAYED α SPECTRUM OF ^{17}N

Initially, α activity attributed to ^{17}N was observed at the mass $A = 17$ separator position in conjunction with the shorter-lived activity of ^{17}Ne. For final data acquisition, the ^{17}N yield was maximized at $A = 33$. This mass position contained the least amount of contaminant activity (^{16}N and ^{18}N) relative to ^{17}N, which was presumably separated as the ^{17}N^{16}O$^+$ molecule. Prior to the run, all six detectors were energy calibrated using the known [7,8] monoenergetic α lines of ^{18}N [$E_\alpha = 1.083 \pm 0.004$ MeV and $E_\alpha = 1.409 \pm 0.003$ MeV (lab)] mass separated as ^{18}N^{16}O$^+$ ($A = 34$). During the 26 h data acquisition, ^{18}N α particles were also observed in the first and second detector pair spectra, allowing a check of the energy calibration. In order to obtain a ^{17}N β-delayed α spectrum free of ^{18}N, only events occurring after 11 half-lives of ^{18}N were used. A small amount of ^{16}N contamination above $E_\alpha = 1.6$ MeV did not obscure the ^{17}N spectrum. The assignment of the remaining α activity to the decay of ^{17}N was in part based on a least-squares fit to the total α activity (in the third detector pair) as a function of time. The determined value of 3.92 ± 0.44 s was in good agreement with the accepted 4.173 ± 0.004 s half-life of ^{17}N [2]. In Fig. 2 both the energy and time distributions of the alpha events recorded at the three detector stations are shown. The summed β-delayed α spectrum of ^{17}N is displayed in Fig. 3.

IV. DATA ANALYSIS

A. K-matrix analysis

The spectrum was fitted using the K-matrix parametrization of Ref. [9] as extended to β-delayed α decay in Ref. [10]. Ref. [10] dealt specifically with the decay of ^{16}N; the relevant equations given there have been modified for ^{17}N decay to take into account the strong neutron decay channel as well as the differing angular momenta. The following equation describes the spectrum of α particles following ^{17}N decay given the assumptions (i) β decay to allowed states ($J^\pi = \frac{1}{2}^-$ or $\frac{3}{2}^-$) only, and (ii) neutron emission is the dominant decay mode:

$$W_\alpha(E) = \sum_{l=0,2} f_\beta(E) p^2_{l\alpha}(E) \left| \frac{\sum_i B_{li} g_{l\alpha i}/(E_{li} - E)}{1 - i p^2_{1n}(E) K_{lnn}} \right|^2 , \tag{1}$$

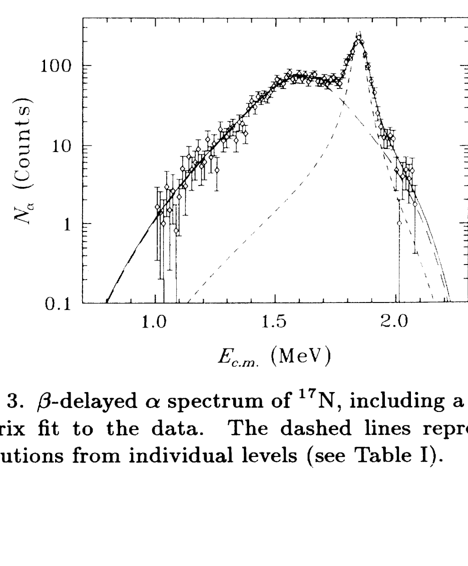

FIG. 3. β-delayed α spectrum of ^{17}N, including a two-level K-matrix fit to the data. The dashed lines represent the contributions from individual levels (see Table I).

$$K_{lnn} = \sum_i \frac{g_{lni}^2}{E_{li} - E}, \tag{2}$$

where the subscript l refers to the orbital angular momentum for alpha decay of the ^{17}O state ($l = 0$ and 2 for $J^\pi = \frac{1}{2}^-$ and $\frac{3}{2}^-$, respectively), $f_\beta(E)$ is the integrated Fermi distribution, $p_{mc}^2(E)$ is the K-matrix penetrability [9] for channel c with orbital momentum m ($m = 1$ for the neutron channel in both J^π cases), E_{li} is the energy of the state i, g_{lci} is the K-matrix partial amplitude of state i for channel c, and B_{li} is the β-feeding factor into state i.

Equation (1) was convoluted with the detector resolution before comparison to the α-particle spectrum. This resolution was treated as a variable parameter in the fits with the measured resolution of 35 ± 10 keV [full width at half maximum (FWHM)] being included as an additional data point. This allowed the uncertainties due to the resolution to be included in the calculation of the errors (defined as the point at which the χ^2 increased by 1.0). Errors in the calibration using the two ^{18}N lines were incorporated in a similar fashion.

Because of the large statistical error for many data points, an iterative fitting procedure was used in which the errors assigned to the data points were taken to be the square root of the points calculated from the previous fit, rather than the square root of the actual numbers of counts.

The initial fit was performed assuming the existence of only two states, with three parameters being varied for each: E_{li}, g_{lni}, and the product $B_{li}g_{l\alpha i}$. This two-level fit, with a χ^2 for 57.3 for 77 degrees of freedom, is shown in Fig. 3. The spectrum consists of one broad and one narrow resonance at $E_{\text{c.m.}} = 1.629$ and 1.844 MeV, respectively. These energies correspond to excited states in ^{17}O previously identified in ^{13}C(α, n) and ^{16}O(n, n) studies [11,12]. The state energies and neutron widths (as determined by the K-matrix analysis) are presented in Table I together with the results of the R-matrix analysis results of Ref. [12]. Assuming allowed β transitions to both states (see logft values in Table II) and given the fact that neither resonance shows an interference pattern, the J^π assignments of Ref. [12] are consistent with our fits of $J^\pi = \frac{1}{2}^-$ or $\frac{3}{2}^-$.

References [2] and [12] indicate the presence of two other levels that may influence the ^{17}N α spectrum: a broad ($\Gamma_{ln} = 560 \pm 60$ keV) $\frac{3}{2}^-$ state at $E_x = 7.56 \pm 0.02$ MeV and possibly a state at 8.18 ± 0.02 MeV with $J^\pi = \frac{1}{2}^-$ ($\Gamma_{ln} = 79 \pm 8$ keV). Although these levels have small alpha widths compared with the states already seen, making the products $B_{li}g_{l\alpha i}$ likely to be negligible, they can affect the fit through interference in Eq. (2). Additional fits were performed incorporating these states.

TABLE I. Alpha-emitting states populated by ^{17}N β decay.

	$E_x[^{17}\text{O}]$ (MeV)		Γ_x (keV)	
J^π	This work[a]	Ref. [12][b]	This work[a]	Ref. [12][b]
$\frac{1}{2}^-$	7.985±0.015	7.990±0.050	407±33	390±39
$\frac{3}{2}^-$	8.204±0.006	8.197±0.008	43±10	53±5.3

[a]From a K-matrix analysis; width defined as $2p_{ln}^2 g_{ln}^2$.
[b]From an R-matrix analysis; width defined as $2P_n\gamma_{\lambda n}^2$.

The broad $\frac{3}{2}^-$ state ($E_{\text{c.m.}} = 1.20$ MeV) was included with its energy and neutron width fixed at the literature values and $B_{2i}g_{2\alpha i} = 0$. Interference caused the narrow state at 8.20 MeV ($E_{\text{c.m.}} = 1.84$ MeV) to be shifted up in resonance energy by 12 keV and to be broadened by 14 keV. The χ^2 increased slightly to 57.8. The broad $\frac{1}{2}^-$ state was unaffected.

Incorporating the 8.18 MeV $\frac{1}{2}^-$ state proved difficult, as it is located within the energy region of the intense 8.20 MeV $\frac{3}{2}^-$ peak, and the interference with the broad $\frac{1}{2}^-$ state takes the form of a sharp minimum, narrower than the experimental resolution. The existence of this level is supported only by the neutron work of Ref. [12], where it was introduced to account for large cross sections at $E_x = 8.2$ MeV. A fit with fixed parameters, as was done for the broad state, gave a χ^2 of 62.9. A χ^2 of 58.5 could be obtained by allowing $B_{0\alpha i}g_{0\alpha i}$ to vary, but the best fit appeared to minimize the effect of the state on the observed spectrum. We conclude that the presence of this level in ^{17}O is not supported by the ^{17}N $\beta\alpha$-decay data.

B. Branching ratios

The determination of the absolute β branching to the α-emitting states in ^{17}O was based on the relative amounts of ^{17}N and ^{18}N, and the known decay of ^{18}N [7]. The production yields of the three nitrogen isotopes present in the $A = 33$ beam were determined by gamma counting the ion beam intercepted by a movable Faraday cup situated 0.5 m upstream of the final collector station. A Ge(Li) detector was used to determined ^{16}N, ^{17}N, and ^{18}N yields of $(1.9 \pm 0.5) \times 10^3$, $(8.4 \pm 1.2) \times 10^4$, and $(2.9 \pm 0.4) \times 10^3$ nuclei/s, respectively, based on their characteristic gamma rays [13]. The relative intensity ratio of the 871 to 2184 keV gammas of ^{17}N was deter-

TABLE II. Branching ratios of ^{17}N β-delayed α decay.

$E_{\text{c.m.}}$ (MeV)	$\beta\alpha B$ (%)	Γ_α/Γ[a]	βB (%)	logft
1.844±0.006	$(9.8\pm2.0)\times10^{-4}$	0.077±0.008	$(1.3 \pm 0.3) \times 10^{-2}$	4.02 ± 0.11
1.629±0.016	$(1.5 \pm 0.3) \times 10^{-3}$	0.059 ± 0.007	$(2.6 \pm 0.6) \times 10^{-2}$	4.34 ± 0.11
~ 1.2	$< 6.9 \times 10^{-5}$	0.0002	$< 3.5 \times 10^{-1}$	≥ 4.0

[a]References [11,12].

mined to be 11.1±2.2, in agreement with the 9.6 ± 0.4 value determined by Alburger and Wilkinson [14], but not with the values of Silbert and Hopkins [15] or Poletti and Pronko [16] (6.8 ± 0.9 and 6.36 ± 0.20, respectively).

The β-delayed α branching of ^{17}N was determined from the relative α activities of ^{17}N and ^{18}N in the first and second detector pairs and the relative total yields of the two isotopes in the ion beam. The total initial ^{18}N activity ($^{18}A_0$) of the deposited ion beam is given by

$$^{18}A_0 = ^{18}Y(1-\exp\{-\lambda_{18}t\}); \tag{3}$$

where ^{18}Y is the yield of ^{18}N as determined by gamma counting the ion beam, λ_{18} is the decay constant of ^{18}N, and t is the collection time; an analogous relation defines the total activity of ^{17}N. The total initial ^{18}N α activity ($^{18}A_\alpha$) is given by

$$^{18}A_\alpha = ^{18}A_0(^{18}B_\alpha), \tag{4}$$

where $^{18}B_\alpha$ is the total β branching to α-emitting states in ^{18}O. Again, an analogous relation exists for ^{17}N. Since the α-detection efficiency for both isotopes is the same, the ratio of total α activities of ^{18}N and ^{17}N is then given by

$$\frac{^{18}A_\alpha}{^{17}A_\alpha} = \frac{^{18}A_0(^{18}B_\alpha)}{^{17}A_0(^{17}B_\alpha)}. \tag{5}$$

Clearly, the total ^{17}N β-delayed alpha branching ratio ($^{17}B_\alpha$) can be determined from the measured ratios of total activities and alpha activities if the β-delayed α branching of ^{18}N is known.

The β-delayed α branching of ^{18}N was taken at $12.2 \pm 0.6\%$, the sum of the branches of the three dominant alpha peaks in the decay of ^{18}N reported in Ref. [7]. The total $\beta\alpha$-decay branching of ^{17}N was then determined to be $(2.5 \pm 0.4) \times 10^{-5}$ using Eq. (5). The $\beta\alpha$ branches to the individual ^{17}O states were determined by partitioning the total $\beta\alpha$ branching by the relative intensities of the two alpha peaks as determined by the K-matrix analysis. These branching ratios are only lower limits of the β branching to the two ^{17}O states, until account is taken of the competing, dominant, β-delayed neutron emission from these states. Absolute β-decay branches were calculated by using the relevant alpha and total widths of the ^{17}O excited states as determined by Fowler, Johnson, and Feezel [11] and Johnson [12]. The results are presented in Table II with $\log ft$ values as determined using the tables of Gove and Martin [17].

Although two states are sufficient to fit the α spectrum with a K-matrix parametrization, the possibility of an additional β decay to a broad state at 7.56 MeV in ^{17}O cannot be entirely discounted. The small alpha width of this state [11,12] does not allow its α decay to be resolved from that of the broad 7.99 MeV state. An upper limit for the branching ratio to this state has been included in Table II based on the estimate that $\leq 3\%$ (100 counts) of the total α spectrum may result from the decay of this state.

V. COMPARISON WITH ^{17}N MIRROR DECAY

The β-delayed proton decay of ^{17}Ne was reported in detail by Hardy *et al.* [18]. More recently, Borge *et al.* [19] have remeasured the proton spectrum with improved statistics and have, additionally, observed β-delayed α emission. Both studies reported β decay to three states in ^{17}F with $\log ft$ and J^π values that are consistent with an assignment as mirror decays of the present work. Table III shows the comparison with the data of Ref. [19], in which the J^π assignments of the ^{17}F states are based on a $\frac{3}{2}^-$ assignment for the 8.2 MeV (^{17}F) level. This assignment is, in turn, based on the assumption that the 8.2 (^{17}F) MeV state is the mirror level of the 7.56 MeV state in ^{17}O [20]. Consequently, the 8.2 and 7.99 MeV states of ^{17}O would be the mirror levels of the 8.08 and 8.43 MeV states, respectively, of ^{17}F. This assignment is further supported by the fact that no delayed α emission is observed from either the 8.2 MeV state of ^{17}F [19] or the 7.56 MeV state of ^{17}O. Also included in Table III are the corresponding comparisons for the lower-lying negative parity states given in Ref. [19].

TABLE III. Comparison of mirror decays of ^{17}N and ^{17}Ne.[a]

^{17}N decay			^{17}Ne decay			
^{17}O* (MeV)	J^π	$\log ft$	^{17}F* (MeV)	J^π	$\log ft^+$	Asymmetry $\delta = [ft^+/ft^-] - 1$
8.2	$\frac{3}{2}^-$	4.02 ± 0.11	8.08	$\frac{3}{2}^-$	3.93 ± 0.06	-0.19 ± 0.29
7.99	$\frac{1}{2}^-$	4.34 ± 0.11	8.43	$\frac{1}{2}^-$	4.05 ± 0.11	-0.49 ± 0.16
7.56	$\frac{3}{2}^-$	> 4.0	8.2	$\frac{3}{2}^-$	4.51 ± 0.06	< 2.0
5.94	$\frac{1}{2}^-$	4.35 ± 0.03	6.04	$\frac{1}{2}^-$	4.55 ± 0.01	0.58 ± 0.12
5.38	$\frac{3}{2}^-$	3.86 ± 0.02	5.49	$\frac{3}{2}^-$	3.81 ± 0.01	-0.10 ± 0.04
4.55	$\frac{3}{2}^-$	4.41 ± 0.02	4.65	$\frac{3}{2}^-$	4.58 ± 0.01	0.47 ± 0.08
3.06	$\frac{1}{2}^-$	7.08 ± 0.08	3.10	$\frac{1}{2}^-$	7.11 ± 0.11	0.1 ± 0.3

[a]The $\log ft^+$ values for the three highest energy states of ^{17}F have been calculated using the branching ratios given in Ref. [19]. The $\log ft$ and asymmetry values for the four lower energy states of both isotopes are taken from Table 6 of Ref. [19].

VI. SUMMARY

Two weak branches of β-delayed α decay of ^{17}N have been observed through excited states at 8.204 and 7.985 MeV in ^{17}O. These account for (2.5×10^{-3})% of the total ^{17}N decay. The deduced ^{17}O state energies and widths agree well with previous measurements using $^{13}C(\alpha,n)$ and $^{16}O(n,n)$ reactions. In comparing the strengths of the allowed mirror decays in mass 17, it is noted that the transition to the third $\frac{1}{2}^-$ state is substantially stronger in ^{17}N than in ^{17}Ne, whereas the reverse is true of transitions to the second $\frac{1}{2}^-$ states.

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