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Study of the beta-delayed alpha-particle emission of ^{16}N

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The beta-delayed alpha-particle emission of ^{16}N has been studied, with ^{16}N nuclei produced using 80 MeV/nucleon ^{18}O beams on ^{9}Be targets. The ^{16}N secondary nuclei were mass analyzed and separated from the reaction products using the Michigan State University A1200 isotope separator. A detector array, including four thin surface barrier detectors, a *p-i-n* diode, a Ge gamma-ray detector, and a two-dimensional position sensitive parallel plate avalanche counter, was used for implantation and study of the separated nuclei. A beta-decay branching ratio of $(1.3\pm0.3)\times10^{-5}$ to the 1^- state at 9.6 MeV and a centroid of 2.35 ± 0.05 MeV for the beta-delayed alpha-particle emission were measured. These results are essential for the analysis of a high sensitivity measurement at Yale University of the low-energy beta-delayed alpha-particle emission of ^{16}N, and for understanding the ^{12}C$(\alpha,\gamma)^{16}$O reaction in the helium burning process in massive stars.

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I. INTRODUCTION

The beta-delayed alpha-particle emission of ^{16}N has been studied extensively in the late 1960s and early 1970s, due to the interest in possible parity-violating alpha-particle decay in this system [1, 2]. It was later suggested that such data could be used to place a constraint on the astrophysical S factor of the ^{12}C$(\alpha,\gamma)^{16}$O capture reaction [3].

Recent theoretical studies predict the beta-delayed alpha-particle emission of ^{16}N to exhibit a low-energy structure [4–6]. This low-energy peak results from the destructive interference between the bound 1^- state (7.12 MeV) and unbound 1^- states (main contribution from the 1^- state at 9.6 MeV). Its magnitude is directly related to the virtual reduced alpha-particle width of the bound 1^- state. The astrophysical cross section of the ^{12}C$(\alpha,\gamma)^{16}$O capture reaction is dominated by this bound state [7], the magnitude of the low-energy interference peak is therefore directly related to the astrophysical cross section of the ^{12}C$(\alpha,\gamma)^{16}$O capture reaction. The beta-delayed alpha-particle emission of ^{16}N in the entire energy region has been measured recently, and the experimental results revealed the existence of this low-energy structure [8–11].

To obtain the astrophysical S factor of the ^{12}C$(\alpha,\gamma)^{16}$O capture reaction, it is required to fit the beta-delayed alpha-particle spectrum of ^{16}N simultaneously with direct measurements of the ^{12}C$(\alpha,\gamma)^{16}$O capture reaction cross section (measured at higher energy) and the phase shift of elastic scattering of alpha-particles from ^{12}C nuclei. In both the R-matrix [5] and K-matrix [6] analyses, the beta-decay branching ratio to the 1^- state is needed for the normalization of the beta-delayed alpha-particle spectrum. This branching ratio was measured to be $(1.20\pm0.05)\times10^{-5}$ [12, 13]. The importance of understanding of astrophysical S factor of the ^{12}C$(\alpha,\gamma)^{16}$O capture reaction warrants a remeasurement of this branching ratio. In this paper we report on a measurement of this branching ratio with results which are consistent with the previous measurements [12, 13].

In an earlier experiment carried out at Yale University, the beta-delayed alpha-particle spectrum was measured to energies as low as E_L=0.6 MeV. The ^{16}N nuclei were produced and stopped in a production target which served as a catcher foil. The centroid of the alpha-particle spectrum, measured in the Yale experiment, was shifted due to the alpha-particle energy loss in the catcher foil. In the present work, the ^{16}N nuclei were implanted and decay inside the detectors; hence the centroid of the alpha-particle spectrum was accurately measured. Therefore, the measurement reported in this paper is essential to calculating the correction applied to the Yale data due to the energy loss of alpha particles in the foil [8–10].

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II. EXPERIMENTAL PROCEDURES

The ^{16}N nuclei were produced using 80 MeV/nucleon ^{18}O beams, from the Michigan State University (MSU) K1200 superconducting cyclotron, on ^{9}Be targets. The secondary nuclei were mass analyzed and separated from the rest of the reaction products using the A1200 isotope separator operated in a momentum-loss achromatic mode and transported into a remote experimental vault for study [14]. The secondary nuclei were then implanted into an array consisting of four silicon surface barrier detectors. The efficiency for the beta-delayed alpha particles decaying inside the detector is nearly 100% and the losses, due to edge effects, were estimated to be below 1.5% [15]. This estimation was confirmed in this experiment [16].

The identification of nuclei supplied by the A1200 isotope separator was achieved by measuring the time of flight of the particles traversing several thin plastic scintillator detectors along the beam line in combination with a two-dimensional position-sensitive parallel-plate avalanche counter (PPAC) and a *p-i-n* diode (ΔE for incoming particles), placed in front of the silicon telescope, as shown in Fig. 1. The obtained secondary beam spot size was on the order of 1–2 cm in diameter. The focal plane detector system consists of a silicon telescope and a high-purity high-efficiency Ge gamma-ray detector. The efficiency of the Ge detector for the full energy peak at 1.3 MeV is 120% with respect to a 7.5 cm NaI(Tl) cylindrical detector. The silicon telescope consists of four thin (25–50 μm) silicon surface barrier detectors tilted at 45° to the incident beam, in order to increase the effective thickness of the thin Si detectors for stopped ^{16}N nuclei. The incoming ^{16}N beam was degraded using aluminum foils before entering the telescope and the beam was collimated in order to remove edge effects in the silicon detectors. The Ge detector was collimated by a lead collimator approximately 10 cm thick (see Fig. 1), and so the Ge detector viewed the telescope array only. The Ge detector collimation efficiency was measured to be better than 99% at 1 MeV. The absolute and relative efficiencies of the Ge detector were measured using calibrated ^{65}Zn (1.116 MeV), ^{228}Th (2.614 MeV), and ^{152}Eu sources. The efficiency was measured at the location of each Si detector, with typical absolute efficiency for 1 MeV gamma rays of approximately 0.1%.

The beam-on and beam-off cycles were controlled by two gate and delay generators in a loop with a period of 10 s. The signals from each alpha-particle detector were sent into two different spectroscopy amplifiers and two separate channels on different ADC modules. The signals for beam-on and beam-off cycles were recorded by a bit-pattern register. The data were recorded, event by event, onto magnetic tapes at the National Superconducting Cyclotron Laboratory at Michigan State Uni-

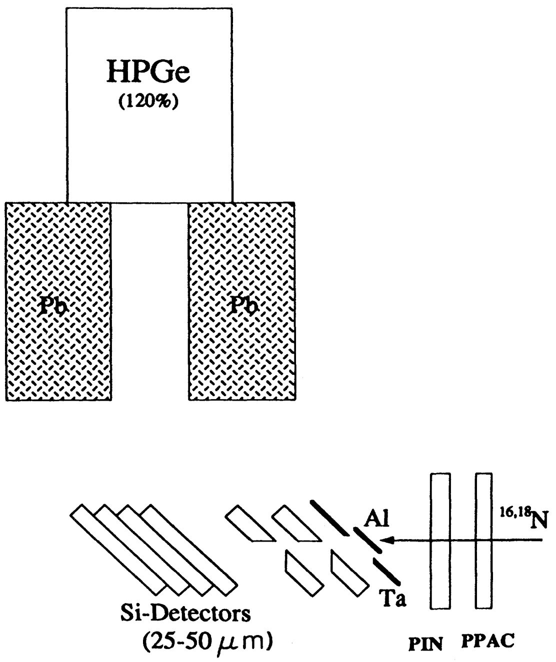

FIG. 1. Experimental setup at the MSU-A1200 focal plane (drawn to scale). Note the lead collimator has an opening of 3.8 cm in diameter.

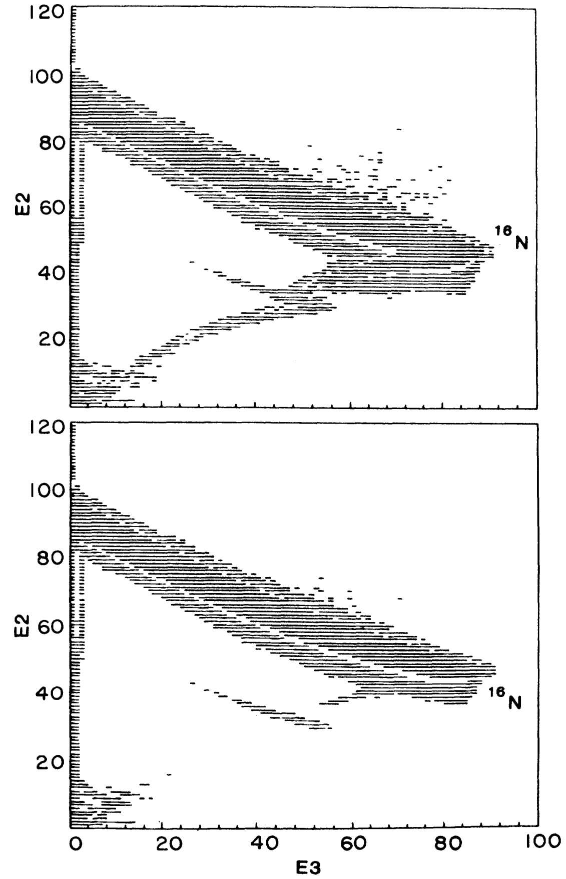

FIG. 2. Typical two-dimensional spectrum of $E2$ vs $E3$, where $E2$ and $E3$ are the energies deposited in the second and third detector in the telescope(top), and $E2$ vs $E3$ with a veto on $E4$ as discussed in text (bottom).

versity and analyzed offline at the A.W. Wright Nuclear Structure Laboratory at Yale University.

III. EXPERIMENTAL RESULTS

The energy spectra of secondary beams were measured during the beam-on period. In Fig. 2 we show a resulting two-dimensional histogram of $E2$ vs $E3$, where $E2$ and $E3$ are energy signals from the second and third Si detectors in the telescope array (see Fig. 1). In the lower panel of the same figure, we also show the same data with a veto imposed by the output of the subsequent detector $E4$, the fourth detector in the telescope. The number of ^{16}N nuclei stopped in the detector $E3$ was deduced from Fig. 2. Note the ^{16}N nuclei which are stopped in dead layers between the detectors are not vetoed in this way. This leads to a small tail visible in Fig. 2. This tail is estimated to be less than 0.1%.

During the beam-off period, the beta-delayed alpha-particle decay spectrum was collected for each detector. Energy calibration of Si detectors, in the beam-off mode, was achieved by examining the beta-delayed alpha-particle emission from ^{18}N which includes two narrow-width lines at 1.40 and 1.82 MeV and one broad line at 2.8 MeV [15].

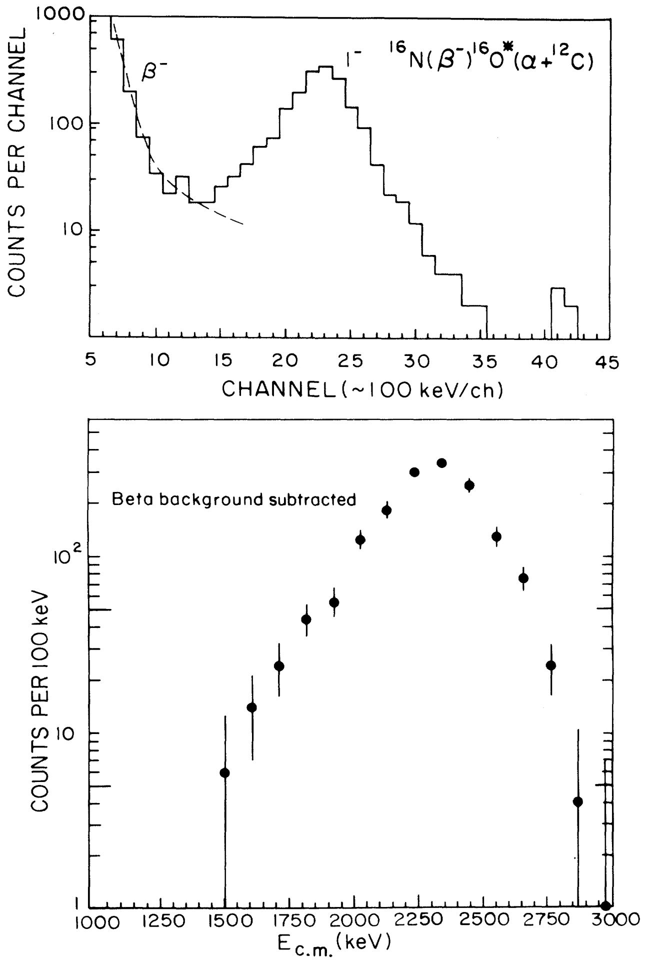

FIG. 3. Typical spectrum of beta-delayed alpha-particles from ^{16}N. In lower panel we show the same spectrum with the background from beta particles subtracted.

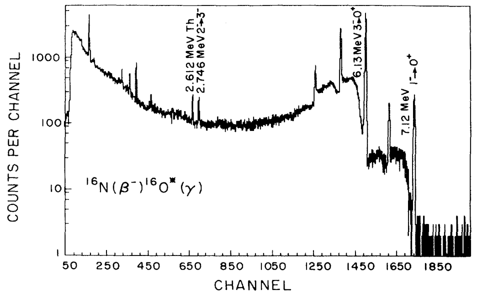

FIG. 4. Beta-delayed gamma rays from ^{16}N. Note the small intensity for the second escape peak, due to the large volume of the detector and the collimator that directs the gamma rays to the center of the detector. Scattering of gamma rays from the collimator is noticeable around 6 MeV.

In Fig. 3 we show the measured beta-delayed alpha-particle spectrum of ^{16}N. The spectrum with background from beta particles subtracted is shown in the lower panel of the same figure. The centroid energy for the broad distribution is measured to be $E_{\text{c.m.}} = 2.35 \pm 0.05$ MeV. By comparing this centroid with the one measured in the Yale experiment, we were able to determine the energy loss of the alpha particles in the catcher foil used in the Yale experiment [8–10].

The beta-delayed gamma-ray emission spectrum was collected using the Ge detector and is shown in Fig. 4. The branching ratio of the beta-delayed alpha-particle decay from the broad 1^- state was extracted by comparing the yield of alpha particles to gamma rays. The total number of alpha-particles in the four Si detectors were summed, being weighted by the gamma-ray effi-

TABLE I. Uncertainties in our measurement.

Source	
Statistical in $E1$	27%
Statistical in $E2$	13%
Statistical in $E3$	6.8%
Statistical in $E4$	18%
Error in Gamma peak	7.4%
Absolute γ eff. for $E1$	2.1%
Absolute γ eff. for $E2$	2.1%
Absolute γ eff. for $E3$	2.2%
Absolute γ eff. for $E4$	2.1%
Weighted subtotal	17%
Error in B.R.(2.74 MeV)	20%
Total	26%

ciency for the location of each Si detector. This sum was then compared to the number of gamma decays recorded in the Ge detector, and the relative branching ratio of alpha-particle decay to the gamma-ray decay was extracted. The source of the errors in this measurement is shown in Table I. The ratio of beta-delayed alpha-particle decays to the beta-delayed 2.746 MeV gamma ray was measured to be $(1.7\pm 0.3)\times 10^{-3}$, which yields the beta-decay branching ratio to the broad 1^- resonance to be $(1.3\pm 0.3)\times 10^{-5}$. Note that we include in the estimate of the error the quoted error of the original measurement of the branching ratio of the 2.746 MeV gamma rays (±20%) [13]. In the above procedure, dead time correction or other effects associated with the beam-on and beam-off cycles are removed by taking the above ratio of alpha-particle and gamma-ray yield, since dead time for two spectra which arise from the data acquisition system are equal. In this way, the extracted branching ratio is solely dependent on the knowledge of the efficiencies and statistical accuracy of the data. The knowledge of the number of ^{16}N nuclei stopped in each detector as defined in Fig. 2 also allows for a measurement of this branching ratio and yields a consistent result with larger uncertainties.

IV. CONCLUSION

The branching ratio for the beta decay of ^{16}N to the unbound 1^- state at 9.6 MeV in ^{16}O was measured to be $(1.3 \pm 0.3) \times 10^{-5}$. This result confirms the previously published result [12]. The extracted matrix element for the beta decay to the unbound 1^- state at 9.6 MeV is approximately a factor of 4 smaller than the one corresponding to the bound 1^- state at 7.12 MeV. In addition, the beta-decay phase space factor strongly favors the low-energy beta-delayed alpha-particle emission. Therefore, an increased sensitivity to the reduced alpha-particle width of the bound 1^- state from the beta-delayed alpha-particle emission of ^{16}N is expected.

The centroid of the beta-delayed alpha-particle emission of ^{16}N was measured to be $E_{\rm c.m.} = 2.35 \pm 0.05$ MeV. From this measurement we can calculate the correction for energy loss in the collection foil used in our earlier experiment at Yale University[8–10]. We note the spectra shown in Fig. 3 exhibit the same centroid as in Refs. [1, 2] at the high-energy points. We observed a low-energy tail in the present work due to alpha particles emitted at the edge of the detectors.

The measured beta-decay branching ratio was used in R-matrix analyses of the Yale data, to extract the astrophysical S factor of the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction [8–10].

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