Beta decay of ^{18}N to alpha particle emitting states in ^{18}O and a proposed search for parity violation in ^{18}O

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The beta-delayed alpha-particle emission from ^{18}N has been studied and the absolute beta decay branching ratios of ^{18}N to the 1_3^- and 1_4^- states in ^{18}O measured. The ^{18}N nuclei were produced using a 35-MeV/nucleon ^{22}Ne beam and a thick Ta target. Reaction products were separated (from the beam) using a reaction products mass separator. A silicon telescope including five detectors and a two-dimensional, position-sensitive, gas counter was used in the focal plane of the mass separator. We obtain beta decay branching ratios of 6.8±0.5 % and 1.8±0.2 % to the 1_3^- and 1_4^- states, respectively, assuming 100% alpha-particle decay branching ratios for these states. Shell-model predictions are compared with these experimental results. The relevance of these data to a new proposed search for parity violation in ^{18}O is discussed.

I. INTRODUCTION

The nucleus ^{18}O has been studied extensively in the past two decades;[1] it provides an excellent environment for the study of nuclear structure and fundamental symmetries because of the simplicity of its nuclear structure.[2] It also appears that ^{18}O constitutes a good candidate for studying parity nonconservation in light nuclei through the study of parity-forbidden alpha-particle decay of its 0^- state at 6.88 MeV.[3]

A proposed experiment to study this process is in progress at Yale University using the ESTU-1 tandem accelerator. The 0^- state at 6.88 MeV in ^{18}O is very similar in nature to the well-studied 0^- state in ^{18}F—a fairly pure $1s_{1/2}0p_{1/2}^{-1}$ configuration, for which the upper limit on the measured circular polarization of the 1.08 MeV gamma deexcitation[4,5] appears to be at least a factor of 3 smaller than the predictions of quark models.[6] Thus, the proposed study of the alpha-particle width of this 0^- state may help us to understand this discrepancy between model predictions and the experimental results for parity nonconservation (PNC) in ^{18}F.

Our proposed experiment is similar in nature to the study of alpha decay of the 2^- state in ^{16}O.[7] In our experiment, the 0^- state at 6.88 MeV in ^{18}O will be populated through the beta decay of ^{18}N. The beta-decay branching ratio to this state was measured by Olness *et al.* to be 15% assuming that the non-gamma emitting branch is 15%.[8] In the case of ^{16}O, the structure of the 2^- decaying state at 8.87 MeV is not well understood, and the PNC alpha-particle decay is difficult to interpret because the mixing arises from several 2^+ states whose structure is not well known. Large experimental backgrounds in this case arise from a broad 1^- state ($\Gamma=510$ keV) at 9.60 MeV. In the case of ^{18}O, our preliminary calculations[9] indicate that the PNC alpha-decaying 0^- state is fairly simple, and that the alpha-particle width is dominated by a constructive addition in terms due to mixing from the 0_2^+ excited state at 3.63 MeV (predominantly $4p$-$2h$ in structure) and the ground state (predominantly a $2p$ state). The 1_3^- state at 7.62 MeV and the 1_4^- state at 8.04 MeV in ^{18}O are expected to contribute to the background of our experiment. Fortunately, this background in our study in ^{18}O will be reduced by several orders of magnitude as compared to the ^{16}O case, because of the narrow width of these close-lying 1^- states. In addition, while in ^{16}O only isoscalar PNC interactions contribute, in ^{18}O both isoscalar and isovector PNC interactions contribute and the PNC effect is proportional to $\sim 1.3F_\pi+F_0$,[9] therefore allowing the possibility of studying the quenching of F_π.[6] The alpha-particle width of the 0^- state at 6.88 MeV is estimated to be of the order of 10^{-11} eV,[9] smaller than the measured alpha-particle width of the 2^- state in ^{16}O of $(1.03\pm0.28)\times10^{-10}$ eV.[7] Thus, a major effort in our experiment is directed toward reduction of background. In this paper we report on a series of initial measurements relating to this idea that provide the basis for our ongoing PNC study.

We first measured the absolute beta-decay branching ratios from ^{18}N to the 1_3^- and 1_4^- states in ^{18}O and report them here as 6.8±0.5 % and 1.8±0.2 % to the 1_3^- and 1_4^- states, respectively, assuming that $\Gamma=\Gamma_\alpha$ for these states. In addition we observe a broad peak in the beta-delayed alpha-particle decay spectrum from ^{18}N. The total yield of beta-delayed alpha particles corresponding to this broad peak was measured, and it is discussed below.

Our experimental techniques and procedures are discussed in Sec. II. In Sec. III we present data analyses. Theoretical predictions of beta-decay branching ratios are compared with the experimental results in Sec. IV and our conclusions are presented in Sec. V.

II. EXPERIMENTAL PROCEDURES

The ^{18}N nuclei were produced using a 35 MeV/nucleon ^{22}Ne beam, from the Michigan State University (MSU) K-500 superconducting cyclotron, bombarding a thick Ta target. The experimental arrangement is shown in Fig. 1; the MSU Reaction Products Mass Separator (RPMS) (Ref. 10) served to separate and analyze reaction products (mostly fragments of the beam) and transport them to the detector system situated at its focal plane. In the present experiment, reaction products were directly implanted into these focal-plane detectors where delayed charged particles could be detected with essentially 100% efficiency.

In Fig. 1 we show the detector system; it includes a two-dimensional, position-sensitive gas counter and a silicon telescope. The silicon telescope consists of five thin surface-barrier detectors tilted at 45° to the incident particles in order to minimize the energy loss from beta decay and still be thick enough to stop the ^{18}N nuclei. This detector system is placed inside a helium bag to minimize the energy loss of the reaction products between component detectors. The helium gas between adjacent detectors, with a length of approximately 1 cm, corresponds to an areal density of 0.18 mg/cm^2 or to an equivalent depth of 1 μm of Si. This corresponds to the range of about 0.5 MeV ^{18}N ions. It is then clear that the helium gas will not perturb our counting of ^{18}N nuclei by more than 1.5%, assuming that reaction products stop through the detector length with equal probability, as would be expected since these recoiling nuclei, transmitted through the RPMS, have a broad energy (velocity) spectrum.

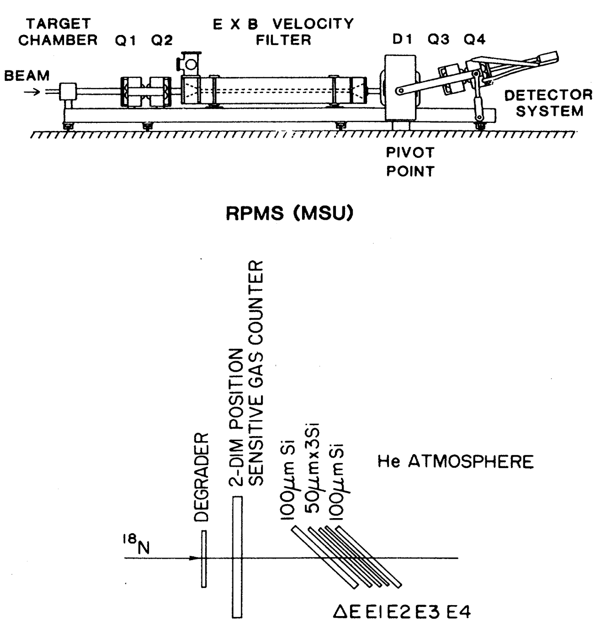

FIG. 1. The MSU Reaction Products Mass Separator (RPMS) used in the present experiment to separate and analyze reaction products. In the bottom of the figure we show the detector system situated in the focal plane of the RPMS.

A two-dimensional, position-sensitive gas counter was used to identify the reaction products. The horizontal signal from the gas counter is obtained from a charge division and the vertical position from the drift time in the counter. The ratio of the mass to change of the reaction products (m/q) is then proportional to the vertical position signal for our RPMS (Ref. 10) arrangement.

The tuning of the RPMS to optimize selection of ^{18}N nuclei was achieved by using a two-detector telescope ($E-\Delta E$), with ΔE measured with a 100-μm-thick, surface-barrier detector, and E with a 5-mm lithium-drifted silicon detector. Figure 2 shows a typical plot of m/q vs particle identifier (PID) output for the reaction products, where PID is defined as PID $=(E+\Delta E)^{1.78}-E^{1.78}$.[11] After the RPMS was tuned to optimize collection of ^{18}N nuclei, a restricting slit approximately 5 mm wide was inserted in front of the detector system in the focal plane to reduce the rate of species other than ^{18}N.

Data were taken using the five-detector telescope array. A gain switching preamplifier was used to allow variation of the gain between beam-on and beam-off cycles. When the beam was on, the gain of the preamplifier was lowered by a factor of about 10 and the energy spectrum of ^{18}N nuclei was collected. When the beam was off, the preamplifier was switched to its higher-gain mode, allowing collection of the spectrum corresponding to the beta-delayed alpha particles from ^{18}N.

Each cycle was divided into four phases: beam-on, a short dead period, beam-off, and a second short dead period. These were controlled by four gate and delay generators in a loop, and had periods of 1.2, 0.04, 1.3, and 0.04 sec, respectively. The complete four-phase timing sequence was continuously monitored by a scaler module which counts gated pulses from a 2^{18}-Hz (256 kHz) quartz oscillator. Data were collected using a CAMAC crate and VME bus and were recorded, event by event, on magnetic tapes using a VAX750 computer in

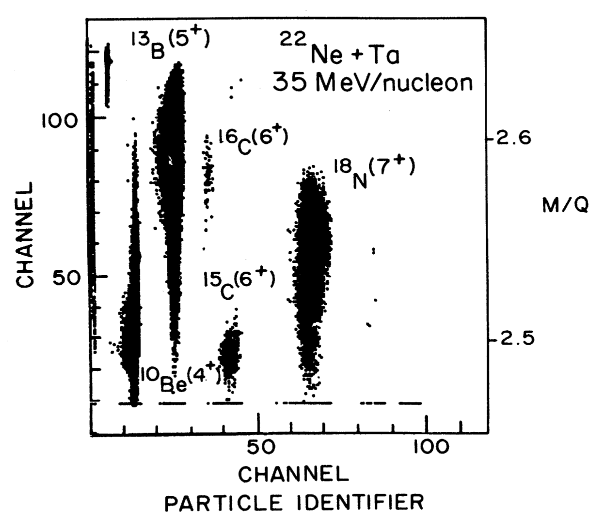

FIG. 2. Mass to charge ratios versus particle identifier signal for reaction products detected in the focal plane, two-dimensional gas counter, and in a $E-\Delta E$ telescope.

the MSU cyclotron laboratory. Off-line analyses was performed at Yale using a Concurrent 3280 computer.

III. DATA ANALYSES

The energy spectra of reaction products were measured during the beam-on period. ^{18}N nuclei were identified by their location at the focal point of the RPMS, as detected in the gas counter. Figure 3 shows a resulting two-dimensional histogram of $E1$ vs $E2$, where $E1$ and $E2$ are energy signals from the second and third detectors in the telescope array, as shown in Fig. 1. Several nuclei with nearby m/q ratios, such as ^{18}N, ^{15}C, ^{13}B, and ^{10}Be, stopped in these detectors, but only ^{18}N nuclei acquire an adequately large Q value to lead to allowed beta-delayed alpha-particle decay. In Fig. 3 we also show the same data but with a veto imposed by the output of the subsequent detector $E3$ (the fourth detector in the telescope array). The number of ^{18}N nuclei stopped in detector 2 was deduced by integrating inside the contour window shown in Fig. 3.

During the beam-off cycle, the beta-delayed alpha-particle decay spectrum was collected. Energy calibra-

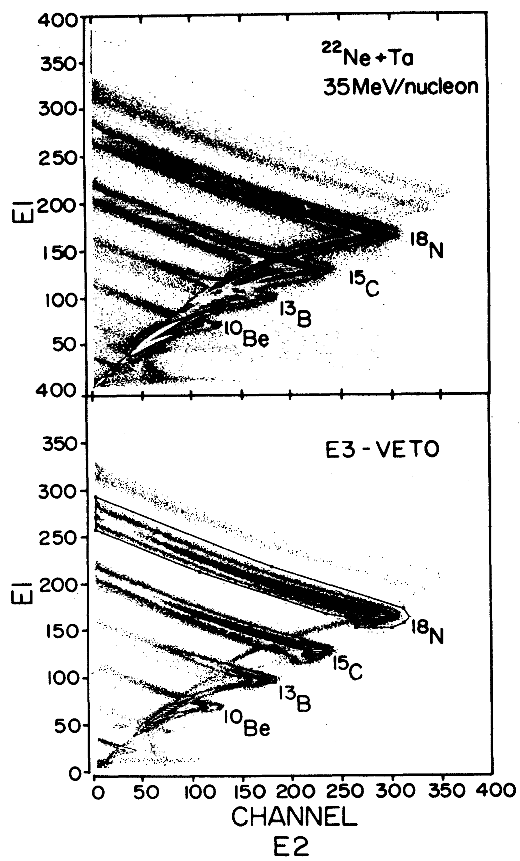

FIG. 3. Typical two-dimensional spectrum of $E1$ vs $E2$ where $E1$ and $E2$ are the outputs of the second and third detectors in the telescope array (top), and $E1$ vs $E2$ with a veto on $E3$ as discussed in the text (bottom). The integration over the indicated contour window was used to extract the number of ^{18}N nuclei stopped in detector $E2$.

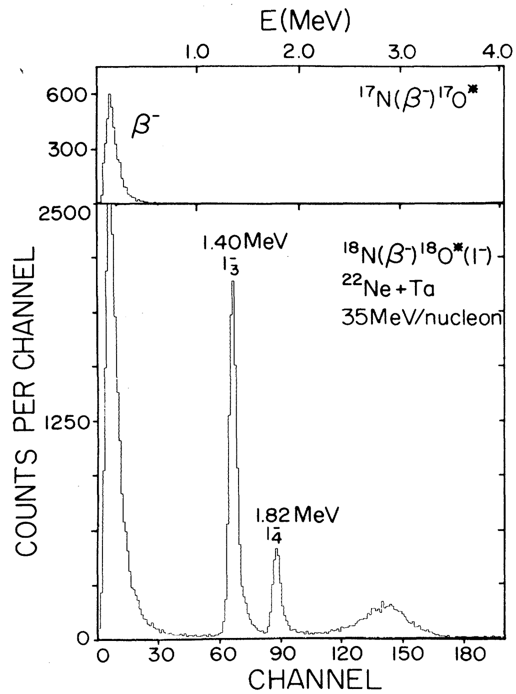

FIG. 4. Typical spectrum of beta-delayed alpha particles from ^{17}N (top) and ^{18}N (bottom).

tion of the surface barrier detectors was achieved by examining well-known beta-delayed alpha-particle emission from ^{11}Be and ^{8}Li nuclei.[12,13] Figure 4 shows the beta-delayed alpha particles from ^{18}N and ^{17}N. The peak at low energy results from the electrons from a variety of beta-decaying reaction products. The alpha-particle decays of the 1_3^- state of ^{18}O at 7.62 MeV and of the 1_4^- state at 8.04 MeV are observed at energies 1.40 and 1.82 MeV, respectively. These energies correspond to the sum of energies of the alpha particles and the recoiling nuclei and include a high-energy tail from contributions from the beta decay itself. The yield of the alpha particles from the 1_3^- and 1_4^- states is deduced from the area of these peaks and the beta-decay branching ratios are calculated as discussed below and as listed in Table I.

The origin of the broad peak near 3 MeV in the alpha-particle spectrum, shown in Fig. 4, is not yet clear. It has been suggested in Ref. 1 that there may, in fact, be six states in ^{18}O that could be depopulated by alpha groups falling in the observed peak. In Fig. 5, we show a detailed fit assuming the existence of these six states; the major fitting parameters and possible states—as suggested in Ref. 1—are given in Table II. In the fitting procedure we assumed that all the broad states interfere in phase with each other. We must note that if this peak instead corresponds to a new, previously unobserved, broad 1^- state in ^{18}O, it will be an important determinant of the background and, therefore, the feasibility of our proposed search for parity nonconservation.[3]

Several corrections to our data are required in order to

TABLE I. Branching ratios (BR) in the decay of ^{18}N.

J_i^π	E_x	Expt. BR[a]	Expt. logft	MK[b] BR	MK[b] logft	MKl[b] BR	MKl[b] logft	MWK[c] BR	MWK[c] logft
1_3^-	7.62	6.8(5)	5.21	3.1	5.77	1.0	6.30	1.0	6.03
1_4^-	8.04	1.8(2)	5.65	0.9	6.17	0.3	6.72	1.4	5.53
1^-	9.00	$\geq$3.6(2)							

[a]All branching ratios are in percent; uncertainties in the last significant figures are given in parentheses. We assume $\Gamma_\alpha/\Gamma=1.0$ for the 1_3^- and 1_4^- states.
[b]As listed in Ref. 9.
[c]B. A. Brown, present calculations.

make possible the extraction of the products of the beta-decay branching ratio and the alpha-particle decay branching ratio for each daughter state. The first, and the most important, correction is that for the efficiency of alpha-particle detection, corresponding to the time window imposed by the beam-off cycle. This correction is given by

$$\epsilon=\frac{\tau e^{-t_2/\tau}(1-e^{-t_1/\tau})(1-e^{-t_3/\tau})}{t_1(1-e^{-t_4/\tau})}, \quad (1)$$

where t_1 and t_3 are the beam-on and beam-off time intervals, respectively, t_2 the time elapsed between the beam-on and beam-off periods (or the time for the preamplifier to switch its gain), $t_4=t_1+t_3+2t_2$, and $\tau=900(17)$ ms is the mean lifetime of ^{18}N.[1] The second correction concerns the uncertainty in determining the number of ^{18}N stopped in the detectors, which arises from an uncertainty in estimating the number of ^{18}N nuclei stopped in the He gas between detectors. This correction was shown above to be smaller than 1.5%. This is smaller than our efficiency and counting uncertainties and we therefore incorporate it in the quoted uncertainty of our results. For ^{18}N nuclei stopped in the dead layer (or in the He gas between the detectors) the sum of the alpha-particle energy and that of the recoiling ^{14}C nucleus cannot be detected, yielding a lower-energy pulse that is not integrated and an alpha particle that is not counted. Also, for ^{18}N nuclei stopped in the detector, it is possible that some decay alpha particles will escape the silicon without leaving their full energy; our Monte Carlo simulation yields an upper limit for this effect at 1%, and we incorporate this to the quoted uncertainty in our branching ratios. The uncertainty in determining the number of alpha particles

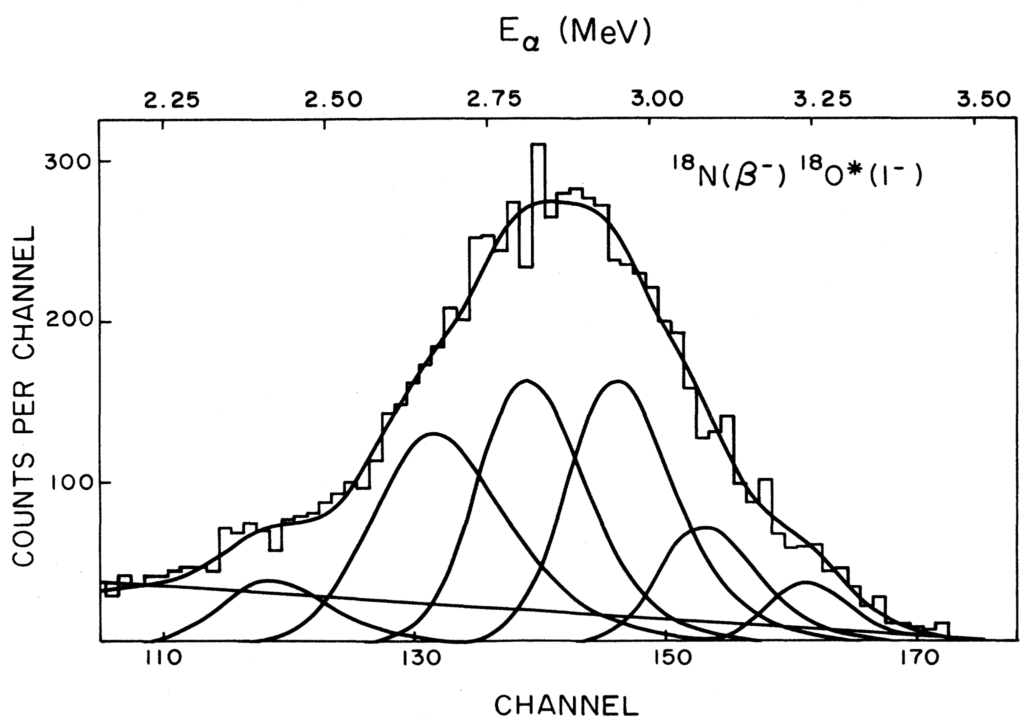

FIG. 5. Decomposition of the broad peak at about 3 MeV into six unresolved alpha-particle groups. The major fitting parameters are listed in Table III and discussed in the text.

TABLE II. Beta decay of ^{18}N to unresolved 1^- states in ^{18}O.

	Present fit[a]		Previous work[c]	
E_x (MeV)	Width (keV)[b]	$BR\times\Gamma_\alpha/\Gamma$ (%)	E_x (MeV)	Width (keV)
8.53(2)	$175(^{+60}_{-20})$	0.21(2)	8.520(6)	
8.79(1)	225(20)	0.98(5)	8.820(12)	70(12)
$8.94(^{+2}_{-1})$	175(20)	0.97(6)	8.960(4)	43(3)
$9.07(^{+1}_{-2})$	$175(^{+120}_{-20})$	0.97(5)	9.03	
9.21(2)	$158(^{+80}_{-20})$	0.35(3)	9.10	
9.36(2)	$142(^{+40}_{-10})$	0.15(2)	9.360(6)	27(15)
	Total	3.63(16)		

[a]Assuming the contributions from the overlapping broad states are all in phase.
[b]Widths are larger or comparable to instrumental widths.
[c]From Ref. 1.

detected (counting statistics) is estimated to be 1.7% for the 1_3^- state and 4.6% for the 1_4^- state. All systematical and statistical uncertainties are summarized and listed in Table III.

For the 1_3^- and 1_4^- states in ^{18}O, we assume that the alpha-particle widths are much larger than the gamma widths and that we can assume $\Gamma=\Gamma_\alpha$. Then the beta-decay branching ratios (BR) in the decay of ^{18}N to these states is given by

$$BR=\frac{N}{N_0\epsilon}\ , \tag{2}$$

where N is the alpha-particle yield from the 1_3^- or 1_4^- states measured during the beam-off cycles, and N_0 is the number of ^{18}N nuclei stopped in the detector and measured during the beam-on periods. The beta-decay branching ratios to the 1_3^- and 1_4^- states and their logft values are extracted in this way and listed in Table I.

For the broad peak near 3 MeV, a beta-decay branching ratio cannot be determined since the corresponding state or states are above the neutron threshold and are expected to have a neutron width larger than, or at least comparable with, the alpha-particle width. The broad peak can only include the 1^- state or states, since the present experiment is only sensitive to decays into natural-parity states and, in first order, only 1^- states are populated since the ground state of ^{18}N has $J^\pi=1^-$.[8] The product of the beta-decay branching ratio and the alpha-particle branching ratio corresponding to this broad peak are given in Table II.

IV. DISCUSSION

Theoretical calculations of the beta-decay branching ratios to the 1_3^- and 1_4 states and the corresponding logft values are listed in Table I where we compare these calculations with our results; all the theoretical predictions appear smaller than the experimental results.

The present experimental results for the decay of 1^- states are combined with the previous beta decay result[8] and compared in Table IV with theoretical calculations of B(GT) value. The experimental reduced Gamow-Teller transition probability B(GT) is given by $6177/ft$, where t is the experimental partial half-life and f is the phase-space factor which was calculated using the tables of Wilkerson and Macefield.[14] The theoretical expression for B(GT) is given in Ref. 15 and is proportional to the square of the matrix element for the operator $|g_A/g_V|\sigma\tau$. We use the empirical value of $|g_A/g_V|=1.251\sqrt{0.6}$, where the factor of 0.6 takes into account the average quenching fund for sd shell nuclei.[15]

All of the theoretical calculations are based on the full set of $(0s)^4(0p)^{11}(1s0d)^3$ configurations for the initial 1^- $T=2$ state in ^{18}N and $(0s)^4(0p)^{11}(1s0d)^3$ $+(0s)^4(0p)^{12}(1s0d)^1(1p0f)^1$ configurations for the final 1^- $T=1$ states. Three calculations are compared in Table IV. The first two are from the original paper of Olness *et al.*,[8] where the results with two effective interactions were compared. The Millener-Kurath-Chung-Wildenthal (MKCW) interaction consisted of the Millener-Kurath (MK) interaction[16] between the $0p$ and $1s0d$ shells and the Chung-Wildenthal (CW) interaction[17]

TABLE III. Uncertainties in our data.

Source	1_3^-	1_4^-	Broad peak
Alpha-particle counting statistics	1.7%	4.6%	3.5%
^{18}N counting statistics	2.0%	2.0%	2.0%
Efficiency for alpha-particle counting	6.0%	6.0%	6.0%
Dead layer and He-gas absorption	1.5%	1.5%	1.5%
Alpha-particle escape	1.0%	1.0%	1.0%
Total	6.8%	8.0%	7.4%

TABLE IV. Experimental and theoretical Gamow-Teller matrix elements for the decay of ^{18}N to 1^- states in ^{18}O.

	Expt.		Theor. MKCW		Theor. MK1CW		Theor. MK3CW	
	E_x (MeV)	B(GT)	E_x (MeV)	B(GT)	E_x (MeV)	B(GT)	E_x (MeV)	B(GT)
1	4.45	0.044(6)	4.45[a]	0.008	4.45[a]	0.007	4.45[a]	0.010
2	6.20	0.0029(6)	6.78	0.022	6.83	0.029	6.85	0.040
3	7.62	0.038(3)	7.79	0.006	7.63	0.002	7.42	0.007
4	8.04	0.0138(12)	8.01	0.002	8.21	0.001	8.04	0.003
1–4		0.099		0.038		0.038		0.060
5	9.00	0.06					8.84	0.001
6							10.34	0.044
7							10.80	0.040
8							11.02	0.013
9							11.33	0.001
10							11.92	0.128

[a]Theoretical energies normalized to experiment for this state.

within the $1s0d$ shell. For the MK1CW interaction the tensor part of the MK interaction was modified.[8] The third interaction (MK3W) is a further update consisting of a new multiranged Yukawa version of MK (with strength parameters chosen to obtain a better fit to the $1p1h$ spectrum of $A=16$)[18] and the new *universal* interaction of Wildenthal for the $0s1d$ shell,[19] labeled MK3CW in Table IV.

The theoretical relative energies of the lowest four 1^- states in ^{18}O are in reasonable agreement with experiment. All the total B(GT) strength for these states is in reasonable agreement. However, the detailed strength distribution is poor for all three calculations. For the MK3W calculation we give individual B(GT) value for the lowest ten states, which shows that there are states with relatively large B(GT) values just several MeV higher than the "Q-value window." One of these may be associated with the broad state observed in this experiment at 9.0 MeV. The total B(GT) strength summed over all 1^- $T=1$ states is 6.63, and the total B(GT) summed over all final $T=1$ states (0^-, 1^-, and 2^-) is 16.53. [The Gamow-Teller strength summed over all final spins and isospins gives $|g_A/g_V|^2 3(N_i - Z_i s) = 18.78$.] Thus, the theoretical strength to these lowest four 1^- states represents only a few percent of the total Gamow-Teller strength. In this context the agreement for the total strength in the lowest four states is impressive. The poor agreement for the individual states may reflect a failure in the details of the spin-dependent interaction components which mix the SU_3 symmetry, as commented on in Ref. 8, or it may reflect the presence of intruder states outside the assumed model space.

An extensive investigation of the beta-delayed gamma-ray emission from ^{18}N has been reported by Olness *et al.*,[8] where it is assumed that the beta-decay branching ratio to non-gamma-emitting states is 15%, as predicted by shell-model calculation. The present experiment shows that the total branching ratio to alpha-particle-emitting states is at least 12.2%. Considering β decay to the ground state and neutron-emitting states, our results may require renormalization of the data of Ref. 8.

V. CONCLUSION

The data presented here allow the extraction of absolute beta-decay branching ratios for the 1_3^- and 1_4^- states of ^{18}O with the assumption that $\Gamma=\Gamma_\alpha$ for these states. These data are important input to the absolute normalization and to the evaluation of the background for our proposed parity-nonconservation experiment in ^{18}O. Appreciable beta-decay yield to a broad bump at 3 MeV is observed and its origin is still unclear. While we treat it as reflecting the presence of several unresolved 1^- states, it is also experimentally consistent with a new broad 1^- state in ^{18}O. Such a broad state would contribute appreciably to the background of our proposed parity-nonconservation experiment.

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