PHYSICAL REVIEW VOLUME 156, NUMBER 4 20 APRIL 1967

Beta-Delayed Protons from Ne^{17} †

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(Received 19 August 1966)

Ne^{17} was produced by the (He^3,$2n$) reaction on thin Al$_2$O$_3$ and gaseous O$_2$ targets, using the 32-MeV He^3 beam of the Brookhaven 60-in. cyclotron. In addition to previously reported delayed proton groups, new groups were observed at center-of-mass energies of 3.72, 6.12, and 10.48 MeV, and the half-life was determined to be 105±5 msec. The highest-energy proton group, which constitutes 0.04% of the total protons observed, corresponds to decay of the analog state of Ne^{17} at an excitation energy of 11.08±0.08 MeV in F^{17}.

INTRODUCTION

Ne^{17} was first identified by Barton and McPherson[1] in 1963 by using the reaction F$^{19}(p,3n)$Ne^{17} on a LiF target. Later work by McPherson, Hardy, and Bell[2] (1964) and Hardy and Bell[3] (1965) established the energies of the most prominent proton groups and determined the half-life to be 103±7 msec. Previously, Karnaukhov *et al.*[4] at Dubna in 1962 recognized delayed proton events following the stripping of 130-MeV Ne^{20} ions by a Ni foil which were later attributed[5] to the decay of Ne^{17}. Other work on Ne^{17} has been given in a preliminary report by Braid *et al.*[6] Preliminary reports of some of the present work have been presented.[7,8] For the most part, the data cited above are in good agreement with those derived in the present work. Some anomalous results attributed to Ne^{17} decay by d'Auria and Preiss remain unexplained.[9] The measurements reported here extend the range of observation to include proton energies from 2.0 to 10.8 MeV ($E_{\text{c.m.}}$). Three new peaks have been observed, and three previously observed[3] but unassigned peaks have been substantiated.

EXPERIMENTAL

Ne^{17} was produced by the (He^3,$2n$) reaction on targets of either gaseous O$_2$ or thin Al$_2$O$_3$, using the 32-MeV external beam of the Brookhaven 60-in. cyclotron. With the exception of the use of a two-detector telescope, the experimental arrangement was substantially the same as that described previously.[10,11] In a typical experiment, the beam was pulsed on for 0.3 sec and then turned off for 0.5 sec during which period pulse-height spectra from protons detected by a surface-barrier silicon detector were stored as a function of time in a two-parameter analyzer. As in previous reports,[10,11] the energy spectrum associated with the half-life of Ne^{17} was resolved from any longer-lived background by use of a least-squares-fitting computer program which analyzed the decay curve of each individual energy channel. For the observation of proton groups at very high energy, use was made of a counter telescope consisting of a thin transmission counter followed by a thick counter in coincidence with it. The sum spectrum was stored in the analyzer. This method achieved a greater effective depletion depth and greatly lowered the background because of the coincidence requirement.

The gas target assembly used a thinner beam entrance window (0.0001-in. Ni) in these experiments than in previous work[11] in order to increase the yield of Ne^{17}, since the excitation function is rising rapidly at our highest energy. Unbacked Al$_2$O$_3$ targets which were 0.3–0.4 mg/cm^2 thick were prepared by anodic oxidation of 0.001-in. Al foil followed by etching of the other side in NaOH to remove the excess Al from the center of the foil. To catch the Ne^{17} recoils these were sometimes backed by 0.2-mg/cm^2 Al leaf. As previously, the plane of a solid target was oriented at 10° to the beam.

An experiment to determine the mass of Ne^{17} was performed. The production threshold of the reaction O^{16}(He^3,$2n$)Ne^{17} was determined by measuring the yield of the main delayed proton peak from a solid target as a function of He^3 beam energy. The incident beam energy was varied in steps from about 26 to 32 MeV using Al degraders. Using a solid state detector to examine the elastic scattering of the beam by a 150-μg/cm^2 Au foil it was possible to monitor the beam energy, energy spread, and intensity during the runs. The yield of the main delayed proton peak was ex-

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† Research performed under the auspices of the U. S. Atomic Energy Commission.

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tracted as before with a two-parameter analysis of the delayed protons. Calibrations of beam intensity were performed at two energies by Mylar foil activation[12] using the reaction $O^{16}(He^3,p)F^{18}$. The beam energy was determined by calibrating the He^3 detector with a Bi^{212} alpha source and by range measurements[13] in Al.

RESULTS

Our best value for the half-life of Ne^{17}, obtained by least-squares fitting of the decay curves for the three main proton peaks in all spectra, was 105±5 msec. Since we obtained consistent half-lives from both the gaseous O_2 and Al_2O_3 targets, this indicates that there is no appreciable diffusion loss of Ne^{17} out of Al_2O_3 as had been observed from Teflon.[2] The weighted average of the other reported values[2,5,6] for the half-life, which are shown in Table I, is 104±4 msec.

Several proton energy spectra are shown in Fig. 1. The appropriate ordinate for a particular spectrum is indicated on either side of the figure. Labeled pulser peaks indicate the respective instrumental resolution appropriate to a particular spectrum (the pulser was not used while obtaining the spectrum shown on the lower right). The number of half-life components used in the resolution of a particular spectrum is also indicated on the figure. The upper curve was obtained from an Al-backed 0.43-mg/cm^2 thick Al_2O_3 target, using a 3 cm^2 in area 6400 Ω-cm resistivity Si surface-barrier detector at 100-V bias. A 6.9-mg/cm^2 Al absorber was placed in front of the detector to stop the alpha particles from the decay of Li^8 which is produced to a small extent in the target. The spectrum fragment in the lower left portion of the figure was taken from a gaseous O_2 target at one atm pressure using two side-by-side detectors at 100-V bias, and is included to show the two small peaks at 3.72 and 4.37 MeV ($E_{c.m.}$). In some previous work[11] it was found that the wire screen which supported the window of the gas target produced some broad low-energy degraded peaks. It is thought that these shoulders are not caused by this effect. The positions expected for the 3.72- and 4.37-MeV proton groups in the upper spectrum are indicated by the unlabeled arrows. The spectrum fragment at the lower right was also obtained from a gaseous target, using the counter-telescope arrangement described above. In this case, the telescope consisted of a detector 1 cm^2 in area and 100 μ thick, operated at sufficient bias for full depletion, followed by a thick detector operated at sufficient bias to enable the telescope to detect protons up to 10.8 MeV ($E_{c.m.}$). The highest energy peak was observed in two other experiments, one of which used a thick Al absorber to verify that the peak was due to protons. Using a single detector at low bias, another spectrum (not shown), obtained from a gaseous O_2 target, did not reveal any additional proton groups in the region 2.0–3.7 MeV ($E_{c.m.}$).

The averaged energies determined for the proton groups are listed in Tables I and II. The values listed ($E_{c.m.}$) include corrections for energy losses in the target, in the window of the gas target if appropriate, and in the recoil of the emitting nucleus. In making the corrections for energy loss of the protons in the Al_2O_3 targets, the effect of the recoil range of Ne^{17} was approximately taken into account using an estimated range along the beam direction of 0.8 mg/cm^2. The errors given include uncertainties in calibration and peak position. Table I compares our values with those reported previously.[2–6] It appears that the energy reported by the Argonne group for the 7.4-MeV peak is in error. The transition intensities given in column 5 of Table II are absolute percentages, since beta decay intensities to the ground and first excited state of F^{17} have been calculated by means of their mirror log*ft* values, and it is expected that we observe very nearly all the other transitions. The estimated beta decay branches to these two bound states are given in the

TABLE I. Comparison of this work with data previously reported for Ne^{17}.

	Brookhaven	McGill[a]	Argonne[b]	Dubna[c]
Half-life (msec)	105 ±5	103 ±7	107 ±5	85 ±15[d]
Major peaks (MeV)	4.05±0.03	4.04±0.06	3.9[e]	
	4.90±0.02	4.87±0.04	4.80±0.05	5.0± 0.2[d]
	5.44±0.02	5.40±0.05	5.3[e]	
Minor peaks (MeV)	3.72±0.03			
	4.37±0.08	4.44[d]		
	5.83±0.08	5.80[d]		
	6.12±0.05			
	7.44±0.03	7.39±0.05	7.03±0.065	
	7.83±0.05	7.81[d]		
	10.48±0.08			

[a] See Refs. 2 and 3. [b] See Ref. 6. [c] See Ref. 5.
[d] Not definitely assigned to Ne^{17} by these authors. [e] Uncertainty in energy not reported.

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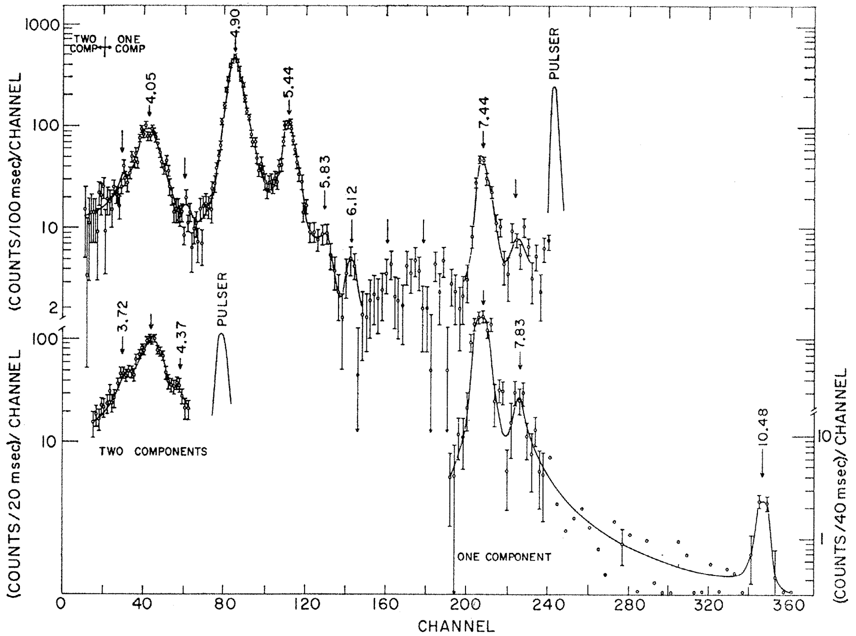

FIG. 1. Beta-delayed proton spectrum of Ne^{17}. Energies are $E_{c.m.}$ in MeV. Upper curve was obtained using an Al_2O_3 target with a 7-mg/cm² Al absorber in front of the detector. Lower left curve was obtained using an O_2 gas target. Lower right curve was obtained using the gas target and a counter telescope.

table. From Fig. 1, it can be seen that the main proton group at 4.90 MeV ($E_{c.m.}$) is somewhat asymmetric. In evaluating the intensity of this peak, however, a symmetrical Gaussian shape was fitted, and the surplus counts (amounting to $\leqslant 4\%$ of the total proton intensity observed) were left unassigned. It should be noted that an open channel for emission of alpha particles to form N^{13} exists at 5.82 MeV above the ground state of F^{17} and that the beta-decay branches to states above this energy may be only lower limits. Log*ft* values were calculated using a value for Q_{β^+} of 14.60 MeV; the determination of this value is discussed below. The decay scheme which we have constructed is shown in Fig. 2. The level scheme of F^{17} is from the compilation of Lauritsen and Ajzenberg-Selove.[14] The spin-parity of Ne^{17} is assumed to be equal to that[15] of its mirror, N^{17}.

TABLE II. Summary of the decay scheme of Ne^{17}.

Level	J^π	Expected $E_{c.m.}$ (MeV)	Experimental $E_{c.m.}$ (MeV)	Proton %	log*ft*[a]
11.08[b]	$\frac{1}{2}-$		10.48±0.08	0.04±0.01	<4.6[f]
		4.43[c] 4.35[c]	4.37±0.08	1.5 ±0.05	$3.1_{-0.1}^{+0.2}$
8.42 8.39		7.82 7.79	7.83±0.05	0.8 ±0.1	4.7 ±0.1[f]
8.06 8.01		7.46 7.41	7.44±0.03	4.5 ±0.4	4.2 ±0.1[f]
7.47[d] to 7.36		6.87 to 6.76		$\leqslant$0.7	$\geqslant$5.1
7.04	$\frac{3}{2}-$	6.44		$\leqslant$0.5	$\geqslant$5.3
6.70	$\frac{3}{2}-$	6.10	6.12±0.05	0.4 ±0.2	5.5 ±0.2
6.43[b]			5.83±0.08	0.9 ±0.3	5.4 ±0.2
6.04	$\frac{1}{2}-$	5.44	5.44±0.02	12.4 ±0.7	4.40±0.03
5.52	$\frac{3}{2}-$	4.92	4.90±0.02	56.2 ±1.8	3.83±0.02
4.69	$\frac{3}{2}-$	4.09	4.05±0.03	19.2 ±1.0	4.50±0.03
4.32[b]			3.72±0.03	2.0 ±0.5	5.6 ±0.1
3.10	$\frac{1}{2}-$	2.50		<1.0	>6.1
0.50	$\frac{1}{2}+$			0.6[e]	[6.87]
0.00	$\frac{5}{2}+$			0.2[e]	[7.29]

[a] Based on $Q_{\beta^+}=14.60$ MeV.
[b] Proposed on the basis of this work.
[c] Energies expected for the transitions from the analog state to the first and second excited states of O^{16}.
[d] Four levels in this region.
[e] Calculated from mirror log*ft* values. See Ref. 15.
[f] Upper limit because of possible unobserved decay channels.

All the energies of the observed proton groups, except those at 3.72, 4.37, 5.83, and 10.48 MeV ($E_{c.m.}$), agree well with the transition energies expected from the level scheme. Additional transitions are expected at recoil-corrected energies of 2.50 and 6.44 MeV, and upper limits for their respective intensities are given in Table II. The absence of these proton groups is consistent with all previous observations. Using the mirror log*ft* value[15] of O^{17} for the transition to the 3.10-MeV level one calculates an expected beta intensity populating this level of only 0.2%, which is well below our level of observation in this energy region. The reason for the large *ft* value for allowed beta-decay of Ne^{17} to this $\frac{1}{2}-$ state in F^{17} has been discussed by Margolis and de Takacsy.[16] The lower limit to the log*ft* value for the 6.44-MeV transition given in Table II is equivalent to that given by Hardy and Bell.[3] A group of four levels in F^{17} at energies of 7.36−7.47 MeV, with unknown spin-parity, might be expected to yield proton groups of 6.76−6.87 MeV; the approximate position of these transitions is indicated by the unlabeled arrow in Fig. 1. The peak at 5.83 MeV ($E_{c.m.}$), which has been noted[3]

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previously, has been assigned as a new level in F^{17} at 6.43 MeV. The transition at 3.72 MeV ($E_{\text{c.m.}}$), though statistically uncertain in the figure, has been observed in a total of 5 experiments and we assign it to another new level in F^{17} at 4.32 MeV. The assignment of the 4.37-MeV transition, which is also poor in statistics but observed in as many experiments, is discussed below.

ANALOG STATE

The energy of the 10.48-MeV proton group was determined from the average of 3 experiments. We attribute this group to proton emission following the superallowed beta decay of Ne^{17} to the isobaric spin $\frac{3}{2}$ analog state in F^{17}. This state has not been located previously but two higher $T=\frac{3}{2}$ levels have been proposed by Hardie, Dangle, and Oppliger[17] on the basis of their $O^{16}(p,p)$ scattering results. By comparing these with the excitation energies of the first two excited states in N^{17}, the lowest $T=\frac{3}{2}$ state in F^{17} is expected to occur at 11.15±0.10-MeV excitation. We observe 11.08 ±0.08 MeV. The observed intensity is lower by about a factor of 25 than the expected value of about 1.0%, using a calculated $\log ft$ value of 3.3 for the superallowed beta transition.[18] However, numerous other channels exist for the decay of this state other than to the ground state of F^{17}, namely to N^{13} by alpha emission, or by proton emission to any or all of the first few excited states of O^{16}. Using optical-model transmission coefficients,[19] one calculates that the analog state branch to the ground state of O^{16} is only about 10% of the total decays of this state. This is based only on the Coulomb and angular momentum barrier and ignores all nuclear structure effects. An attempt was made to observe alpha particles from the analog state, using a 0.28 mg/cm² unbacked Al_2O_3 target and a 65-μ-thick transmission detector with a second detector in anticoincidence to eliminate the proton through-peaks. Interference from Li^8 alpha particles made it impossible to do more than establish an upper limit of 1.2% for alphas from the analog state. However, it is interesting to note that the energy of the 4.37-MeV proton group corresponds within experimental error to the energy expected for decay of the analog state to either the 0^+ or 3^- level in O^{16}. The intensity, though uncertain, is consistent with the $\log ft$ expected for the superallowed transition, as noted in Table II. In Fig. 2, the 4.37-MeV transition is shown as originating from the analog state, although the assignment is only a tentative one. Alternatively, one might assign this transition to a new level in F^{17} at 4.97 MeV, as discussed below.

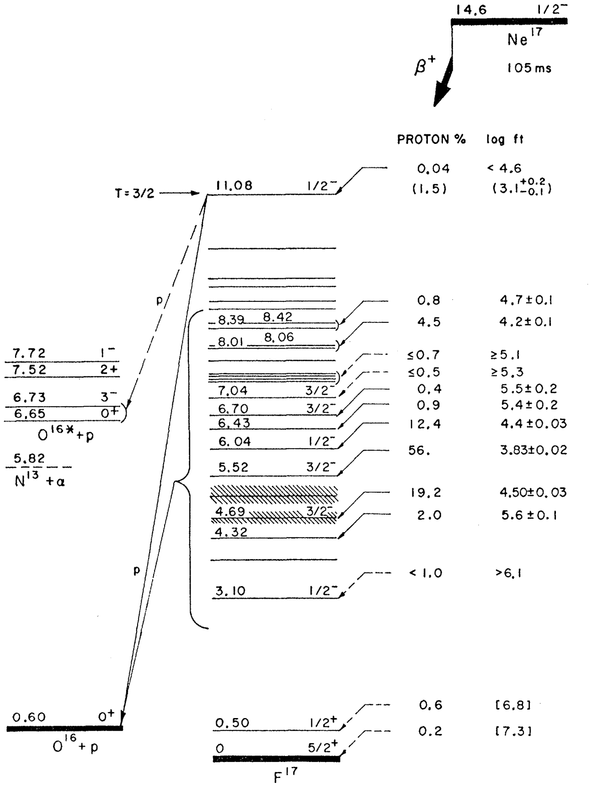

FIG. 2. Proposed decay scheme of Ne^{17}. The percentages denote the proton intensities. For the transitions to the ground and first excited states the beta percentages are calculated from the $\log ft$ values taken from the mirror decay. The numbers in parentheses for the 11.08-MeV level refer to the excited-state proton transition indicated by the dashed line.

BETA-DECAY ENERGY OF Ne^{17}

The relative yield as a function of energy for the reaction $O^{16}(He^3,2n)Ne^{17}$ is shown in Fig. 3. From estimates of the counter geometry, etc. it is likely that the ordinate also represents the absolute cross section in microbarns with an error of about 50%. A reaction threshold was determined from the relative yields. The method outlined by Grover and Nagle[20] was used to correct for the 0.45-MeV spread in beam energy. An iterative least-squares procedure was used to fit the 12 data points from 27 to 30 MeV. Assuming the cross section for the reaction to vary with the square of the energy above threshold in the center-of-mass system, the Q value for the reaction was found to be −22.42 ±0.19 MeV. Using the remaining points up to full energy and allowing the energy exponent to vary, showed that the square dependence was reasonable, within the error, for the form of the excitation function. This reaction Q value corresponds to a Q_{β^+} for the decay

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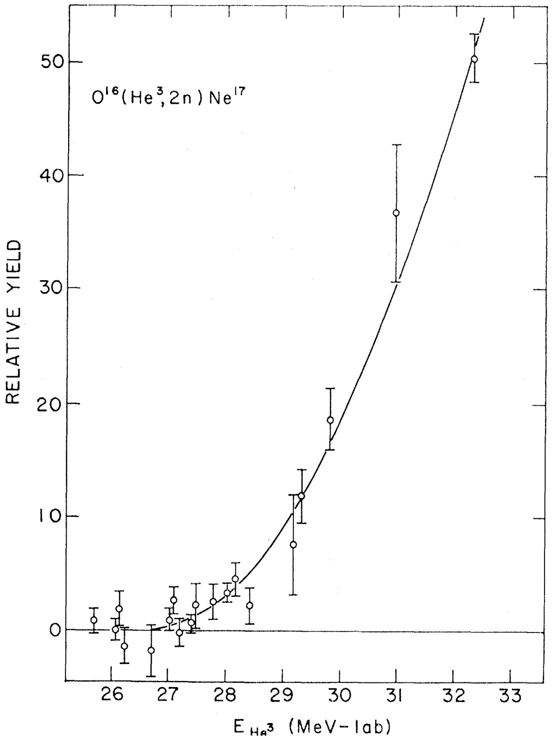

FIG. 3. Excitation function for the reaction $O^{16}(He^3,2n)Ne^{17}$.

of Ne^{17} of 14.52±0.19 MeV using the 1964 atomic mass table.[21]

Wilkinson[22] calculated the Q_{β^+} of Ne^{17} by obtaining consistency with the observed lifetime of Ne^{17} and the mirror log*ft* values[23] modified by the more precise branching ratios measured for Ne^{17} decay. Repeating his calculation with the improved data presented here, we obtain a value for Q_{β^+} of 14.6±0.2 MeV, which compares favorably wlth the value determined from the reaction threshold. Combining the two numbers, and allowing for systematic errors in both methods, we obtain a best experimental Q_{β^+} of 14.56±0.2 MeV. Previous calculated estimates include Jänecke's[24] value of 14.4±0.3 MeV, and an approximation to the isobaric mass formula[22] using ground-state masses which gives 14.2 MeV.

DISCUSSION

The region of levels in F^{17} from about 4.3 to 5.1 MeV has been one of some ambiguity. The situation has been summarized by Manduchi *et al.*[25]: The $\frac{3}{2}-$ level shown in Fig. 2 as occurring at 4.69 MeV has been proposed by Laubenstein and Laubenstein[26] as occurring at 4.73 MeV, by Sempert *et al.*[27] at 4.5 MeV, by Harris *et al.*[28] at 4.60 MeV, and by Salisbury and Richards[29] at 4.69 MeV. In addition, $\frac{3}{2}+$ states have variously been assigned at 4.35 MeV,[26] 4.6 MeV,[27] 4.97 MeV,[28] and 5.101 MeV.[29] Also, a $\frac{1}{2}+$ state[27] has been proposed at 5.1 MeV. Manduchi *et al.*[25] have concluded from measurements of polarization of protons in elastic scattering that the data of Salisbury and Richards[29] are most nearly consistent with their analysis, but the evidence is not conclusive. The problem then of assigning the 4.37-MeV transition either to a new level at 4.97 MeV, or to decay of the analog state to excited states in O^{16} must be left open to question.

Margolis and de Takacsy[16] have performed shell-model calculations for two-particle one-hole levels in the mass-17 system. They have calculated log*ft* values for Ne^{17} beta decay to the predicted negative-parity F^{17} levels and include a comparison with these experimental data.

ACKNOWLEDGMENTS

The authors are grateful to B. Margolis and N. de Takacsy for interesting discussions, to W. C. Hamilton for the use of his iterative least-squares-fitting program, and to Evelyn Sagan for the preparation of the Al_2O_3 targets.

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