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GAMMA DECAY IN ^{19}Ne

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Abstract: The reaction ^{17}O(^{3}He, nγ)^{19}Ne has been studied at incident energies of 3.0, 4.0 and 5.0 MeV. Fourteen previously unreported transitions in ^{19}Ne were identified in n-γ coincidence spectra. Limits on lifetimes for seven levels were determined using the Doppler-shift attenuation method. The analogues in ^{19}F of eight ^{19}Ne states are identified on the basis of γ-ray branchings. It is suggested that the previous report of a state at 4.78 MeV in ^{19}Ne is erroneous and that the state at 4.68 MeV in ^{19}F is the analog of the 4.71 MeV state in ^{19}Ne.

E | NUCLEAR REACTIONS ^{17}O(^{3}He, nγ), E = 3.0, 4.0, and 5.0 MeV; measured E_γ, $\sigma(E, E_\gamma)$, Doppler-shift attenuation, n-γ coin. ^{19}Ne deduced levels, $T_{\frac{1}{2}}$, γ-branching, analog states. Enriched targets.

1. Introduction

The reaction ^{17}O(^{3}He, nγ)^{19}Ne has been used to investigate the poorly known levels of ^{19}Ne in the range E_x = 4.0–5.1 MeV. Measurements of γ-ray energies lead to precise excitation energies for eight levels. Limits on mean life were established for seven levels, using the Doppler-shift attenuation method. In sect. 4, the present data are compared with properties of levels of the considerably better known mirror nucleus ^{19}F. A discrepancy in the number of reported levels in ^{19}F and ^{19}Ne is discussed.

2. Experimental measurements

The reaction ^{17}O(^{3}He, nγ)^{19}Ne was studied at incident energies of 3.0, 4.0 and 5.0 MeV. Beam currents of 30–70 nA were used for individual measurements of 2 to 8 days duration. Gamma rays and neutrons from the reaction were detected in coin-

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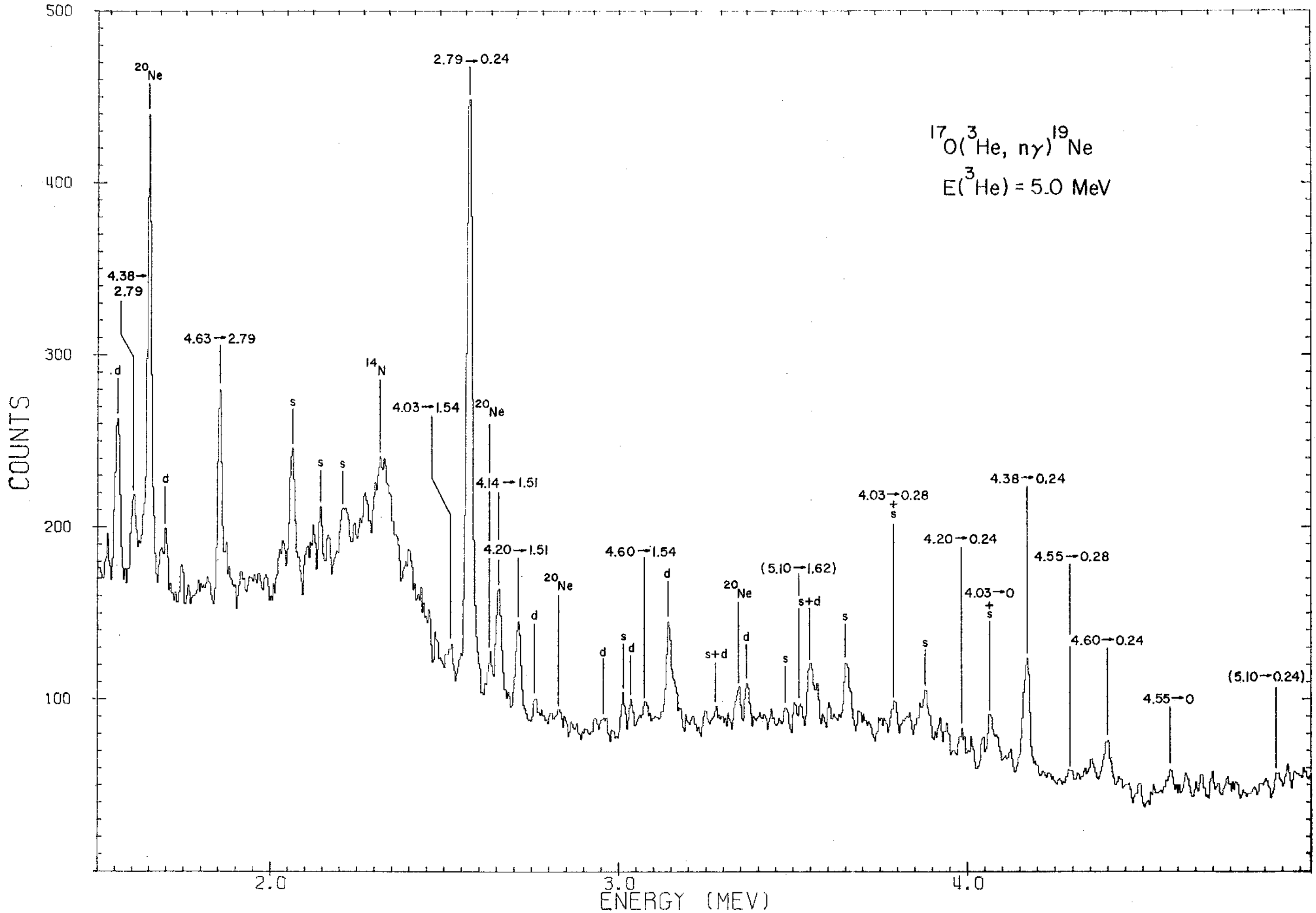

Fig. 1. A sample neutron-coincident γ-ray spectrum is shown. Peaks are labeled according to the transitions in ^{19}Ne. Single and double escape peaks are indicated by the letters "s" and "d" respectively. Peaks arising from the presence of impurities on the target are labeled according to the γ-emitting final nucleus. Three-point smoothing has been done to facilitate visual inspection.

cidence. Neutrons were detected in a 7.5 cm long by 7.5 cm diameter cylindrical NE213 liquid scintillator, with pulse-shape discrimination being used to differentiate neutron from γ-ray interactions. A 50 cm^3 Ge(Li) detector was used and the placement of detectors selected differently for the determination of excitation energies, the measurement of branching ratios, and the lifetime observation by the Doppler-shift attenuation method. A timing resolution of 5.5 ns (FWHM) was attained by the use of a Canberra model 1426 extrapolated zero strobe timing unit on the Ge(Li) signal. The beam current was kept low to limit the counting rate in the Ge(Li) detector to a few thousand counts/s, the rate at which the degradation of the γ-ray energy resolution first became evident. The ratio of true to accidental coincidences thus obtained was greater than 50 : 1. A multi-parameter pulse-height analyser system was used to record coincidence data event by event onto magnetic tape. This data included NE213 pulse-shape information, thus enabling separate examination in later analysis of Ge(Li) pulse-height spectra coincident with either γ-rays or neutrons in the NE213 liquid scintillator. A sample γ-ray pulse-height spectrum, recorded in coincidence with neutrons detected in the NE213 liquid scintillator, is shown in fig. 1. Peaks in this spectrum are identified with various transitions in ^{19}Ne. To identify effects due to ^{18}O and ^{12}C, both of which were present on the targets, separate coincidence spectra were collected using targets of each.

The ^{17}O targets in this work consisted of an approximately 80 $\mu g/cm^2$ thick layer of Ta_2O_5, deposited on a gold backing. The oxygen gas used in the fabrication of the targets was enriched to 62 % in ^{17}O, with 17 % as ^{18}O. Details of the target preparation have been described elsewhere [1]).

Two contaminants on the target, ^{12}C and ^{18}O, gave rise to γ-rays of well known [refs. [2-4])] energy for calibration. These γ-rays, because they were emitted in coincidence with neutrons or with other γ-rays, were accumulated in the coincidence spectra simultaneously with those from ^{19}Ne. The calibration γ-rays were the 2.31, 2.79, and 5.11 MeV γ-rays from ^{12}C(^{3}He, p)^{14}N, the 6.13 MeV γ-ray from ^{18}O(^{3}He, nα) ^{16}O, the 0.87 MeV γ-ray from ^{18}O(^{3}He, α)^{17}O and the 1.63 MeV γ-ray from ^{18}O (^{3}He, n)^{20}Ne. Including the escape peaks of the higher energy γ-rays provided ten calibration points, known to within a few hundred eV. Although some of these peaks were weakly populated, the calibration was better than $\pm$1.5 keV at any point in the recorded spectrum.

3. Results

3.1. GAMMA DECAYS

The electromagnetic decay of states in ^{19}Ne above 3 MeV excitation has not been observed in previous work, with the exception of a single transition. A search was made of the γ-ray pulse-height spectra obtained in this study for evidence of such decays. Fifteen γ-ray transitions were observed with energies consistent with that of expected transitions in ^{19}Ne and are identified with the decay of eight states. These

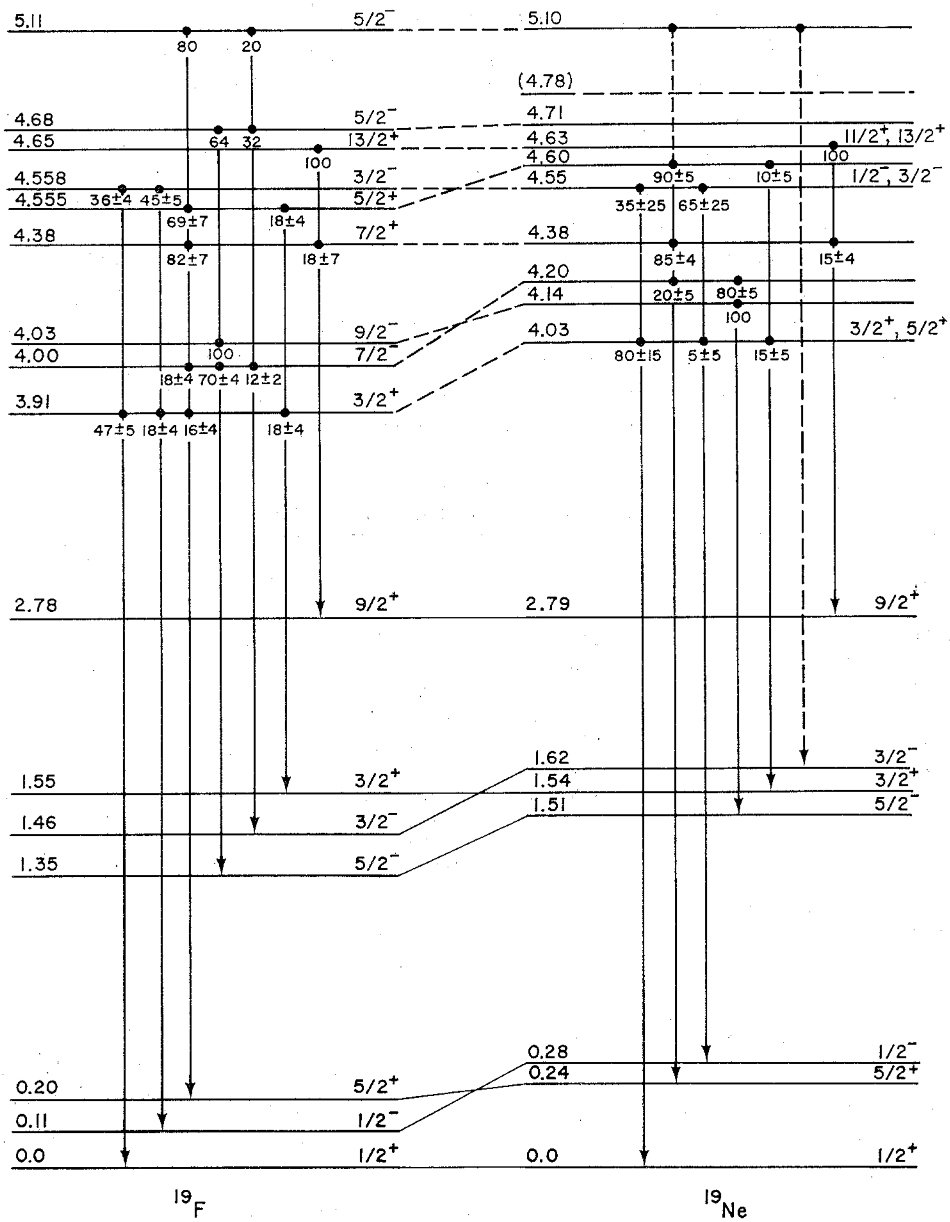

Fig. 2. Observed γ-decay and branching ratios for levels in ^{19}Ne are shown. The mass-19 analogs below 3 MeV and branching ratio data for ^{19}F were selected from ref. [3]). The analogs of the eight levels in ^{19}Ne from which γ-transitions were observed were identified on the basis of γ-branching and are indicated by dashed lines. It is also suggested in the present work that the previous report of a 4.78 MeV level in ^{19}Ne is erroneous, and that the state at 4.68 MeV in ^{19}F is the analog of the state at 4.71 MeV in ^{19}Ne (see subsect. 4.8). The spacing of the levels in this figure is not to scale.

transitions are shown in fig. 2. The transition 4.14 → 1.51 MeV has been previously observed by Olness *et al.* [5]). The nine separate neutron-coincident pulse-height spectra obtained were carefully examined for ^{19}Ne transitions. The stronger transitions were clearly observed in all spectra and twelve transitions evident in all of the longer runs. No evidence was seen for transitions from the levels at 4.71 and 4.78 MeV, or from levels above 5.10 MeV. The identification of the transitions 5.10 → 0.24 and 5.10 → 1.62 MeV is considered tentative, because of the weakness of the observed transitions. To ensure that the peaks observed were due to ^{19}Ne, separate coincidence spectra were recorded using targets of ^{18}O and ^{12}C, the principal contaminants present on the ^{17}O targets. Several neutron-coincident γ-rays were thus identified as resulting from the reaction ^{18}O(^{3}He, nγ)^{20}Ne and are so identified in the spectrum shown in fig. 1. A very strong γ-ray from the reaction ^{12}C(^{3}He, pγ)^{14}N appears as a small peak in this spectrum as a result of imperfect n-γ discrimination.

TABLE 1

Excitation energies (keV) of levels in ^{19}Ne

Present work	^{16}O(^{6}Li, t) [ref. [13])]	^{19}F(^{3}He, t) [ref. [14])]	^{20}Ne(^{3}He, α) [ref. [9])]	^{17}O(^{3}He, n) [ref. [7])]	^{20}Ne(^{3}He, α) [ref. [8])]
4032.9±2.4		4040±8	4036±10	4010±20	4013±15
4140 ±4		4146±8	4142±10	4130±30	4125±15
4197.1±2.4		4208±8	4200±10		
4379.1±2.2		4385±8	4379±10	4360±30	4344±15
4549 ±4		4554±8	4551±10	4540±30	4547±15
4605 ±5	4593±6	4605±8			
4635 ±4		4640±8	4625±10		
		4716±8	4712±10	4690±30	4689±15
			4783±20		
(5097 ±10)		5094±8	5093±10	5090±30	5077±15
Average variance from present work		+4	−0.5	−14	−18

For the branching ratio determinations, detector angles of $\theta_n = +20°$ and $\theta_\gamma = -45°$ were chosen. This allowed placement of the front surface of the Ge(Li) detector 0.15 cm from the reaction site to optimize the coincidence efficiency and the large acceptance angle of the γ-ray detector ($\theta_\gamma = 45° \pm 35°$) reduced the effects of anisotropies in the n-γ angular correlation. Cross sections for n-γ coincidences were measured for this geometry using incident energies of 3.0, 4.0 and 5.0 MeV and have been listed elsewhere by Davidson [6]). Branching ratios for seven levels in ^{19}Ne were computed, based on the measured cross sections, and are indicated in fig. 2.

3.2. EXCITATION ENERGIES

The excitation energies deduced from γ-ray energies are listed in table 1 along with the results of other work. The ^{19}Ne energies were obtained by combining the measured energy of the de-excitation γ-rays with the published values [3]) for the excitation energies of lower states. For the determination of excitation energies, the detectors were placed at $\theta_n = 0°$ and $\theta_\gamma = 90° \pm 2°$. The correction for nuclear recoil upon γ-ray emission was made and a contribution to the uncertainty was included for the uncertainty in angular position of the detector.

The measured excitation energies differ systematically from the values previously reported by Gul *et al.* [7]) and by Greene and Nelson [8]). In both of these cases, the sets of data are in good agreement if the systematic differences are removed, leaving average deviations of 6 and 8 keV respectively.

3.3. LIFETIMES

For the eight strongest transitions, the Doppler-shift attenuation factor $F(\tau)$ was extracted from the first order relation

$$E_\gamma = E_{\gamma 0}(1+F(\tau)\beta \cos\theta).$$

Neutron-γ coincidence spectra were recorded for two geometries: $\theta_n = 0°$, $\theta_\gamma = 90°$ and $\theta_n = -90°$, $\theta_\gamma = 28°$. An incident energy of 5.0 MeV was used. The initial ^{19}Ne recoil velocity and detector angle with respect to the recoil velocity direction were

TABLE 2

Summary of Doppler-shift attenuation measurements

Transition $E_i \to E_f$ (MeV)	$F(\tau)$ (%)	Mean life τ (ps)
4.03 → 0	102±12	< 0.05
4.14 → 1.51	81±26	< 0.30
4.20 → 1.51	74±25	< 0.35
4.38 → 0.24	88±12	< 0.12
4.55 → 0	93±23	< 0.08
4.55 → 0.28	118±25	
4.60 → 0.24	82±13	< 0.16
4.63 → 2.79	6±20	> 1.0

computed from the reaction kinematics for reactions leading to each initial state in table 2. Theoretical curves of $F(\tau)$ versus τ were calculated for ^{19}Ne ions slowing down in gold, with the effects of the thin Ta_2O_5 target layer being neglected. This approach was deemed acceptable, because the average energy loss of the ^{19}Ne ions in the target layer differs from that in an equal layer of the backing material by only 1 % of the initial recoil energy of the ^{19}Ne ions. The results are summarized in table 2. Transitions for the levels at 4.03, 4.14, 4.20, 4.38, 4.55 and 4.60 MeV all yielded $F(\tau)$ values consistent with 1.0, with differing lower limits. The transition 4.63 → 2.79 MeV showed very little Doppler shift, indicating a relatively long mean life (see subsect. 4.6). For the level at 4.55 MeV, values of $F(\tau)$ were extracted for two transitions, and the weighted mean was adopted in determining the limit on τ.

4. Discussion

Identification of isobaric analog states in the mirror pair ^{19}F and ^{19}Ne has been suggested in previous work for five states in the range of excitation from 3.9 to 5.1 MeV. These determinations have been made on the basis of angular momentum transfer measurements [9,10]) in the reactions ^{20}Ne(^{3}He, α)^{19}Ne and ^{16}O(^{6}Li, t)^{19}Ne, and on the basis of cross section measurements [11]) in the mirror reactions ^{16}O(^{6}Li, t)^{19}Ne and ^{16}O(^{6}Li, ^{3}He)^{19}F. Identification of isobaric analogs is now made, based on a comparison of the γ-ray branchings observed for states in ^{19}Ne with the decay schemes previously observed [3]) for states in ^{19}F. Identification of analogs is thus made for nine pairs of levels in the range of excitation from 3.9 to 5.1 MeV. The assignments for the states at 4.14, 4.20, 4.60 and 4.71 MeV excitation in ^{19}Ne are new assignments; the assignments made for the states at 4.03, 4.38, 4.55, 4.63 and 5.10 MeV excitation in ^{19}Ne are consistent with those suggested in previous works [9–11]). All discussion in subsects. 4.1 to 4.8 refers to fig. 2.

4.1. The level at 4.03 MeV. The 4.03 MeV level of ^{19}Ne ($J^{\pi} = \frac{3}{2}^{+}, \frac{5}{2}^{+}$) and the 3.91 MeV level of ^{19}F ($J^{\pi} = \frac{3}{2}^{+}$) are the only levels near 4.0 MeV having a predominant ground-state decay. The weaker branches observed, 4.03 → 0.28 and 4.03 → 1.54 MeV, support this analog identification.

4.2. The levels at 4.14 and 4.20 MeV. The 4.14 and 4.20 MeV levels of ^{19}Ne and the 4.00 and 4.03 MeV levels of ^{19}F ($J^{\pi} = \frac{7}{2}^{-}$ and $\frac{9}{2}^{-}$ respectively) are the only levels near 4.2 MeV which decay predominantly to the $\frac{5}{2}^{-}$ level near 1.5 MeV. The branch, 4.20 → 0.24 MeV, identifies the 4.20 MeV level of ^{19}Ne with the 4.00 MeV level of ^{19}F. The 4.14 MeV level of ^{19}Ne is thus identified as the analog of the 4.03 MeV level of ^{19}F. It is noted that the ordering of the 4.14 and 4.20 MeV levels of ^{19}Ne is reversed from that of their analogs in ^{19}F. These states are those formed by the coupling of a $p_{\frac{1}{2}}$ hole with the 4^{+} member of the ground state rotational band of ^{20}Ne. It is surprising to see the $\frac{7}{2}^{-}$ member lower in ^{19}F.

4.3. The level at 4.38 MeV. The 4.38 MeV level of ^{19}Ne and the 4.38 MeV level of ^{19}F ($J^{\pi} = \frac{7}{2}^{+}$) are the only levels near 4.4 MeV which decay predominantly to the $\frac{5}{2}^{+}$ member of the ground state triplet. The weaker branch 4.38 → 2.79 MeV supports this analog identification.

4.4. The level at 4.55 MeV. The 4.55 MeV level of ^{19}Ne ($J^{\pi} = \frac{1}{2}^{-}, \frac{3}{2}^{-}$) and the 4.558 MeV level of ^{19}F ($J^{\pi} = \frac{3}{2}^{-}$) are the only levels near 4.6 MeV which decay predominantly to the $\frac{1}{2}^{-}$ member of the ground state triplet. The weaker transition observed leading from this level to the ground state supports this analog identification.

4.5. The level at 4.60 MeV. The 4.60 MeV level of ^{19}Ne and the 4.555 MeV level of ^{19}F ($J^{\pi} = \frac{5}{2}^{+}$) are the only levels near 4.6 MeV which decay predominantly to the $\frac{5}{2}^{+}$ member of the ground state triplet. Additional support for this analog identification is provided by the weaker 4.60 → 1.54 MeV branch.

4.6. The level at 4.63 MeV. Indication that the 4.63 MeV level in ^{19}Ne is a state of angular momentum $J > \frac{7}{2}$ is contained in the fact that its γ-decay proceeds to a state of angular momentum $\frac{9}{2}$ in preference to available states of $J^\pi = \frac{1}{2}^\pm, \frac{3}{2}^\pm$, and $\frac{5}{2}^\pm$ lying at still lower energies. A lifetime in excess of 1 ps is consistent with $J \geqq \frac{13}{2}$, using the single particle widths of Wilkinson [12]). For $J = \frac{9}{2}$ or $\frac{11}{2}$, a value of $|M|^2 \leqq 5\times10^{-3}$ would be required for M1 transitions or $|M|^2 \leqq 2\times10^{-4}$ for E1 transitions. Such small values are rarely observed in the light nuclei. Thus, it is likely that the 4.63 MeV level is a state of angular momentum $J \geqq \frac{13}{2}$. The 4.63 MeV level in ^{19}Ne and the 4.65 MeV level in ^{19}F ($J^\pi = \frac{13}{2}^+$ and $\tau_m = 2.2\pm0.3$ ps) are the only levels near 4.6 MeV which decay predominantly to the $\frac{9}{2}^+$ level near 2.8 MeV, and whose lifetimes exceed 1 ps.

4.7. The level at 5.10 MeV. The 5.10 MeV level of ^{19}Ne and the 5.11 MeV level of ^{19}F ($J^\pi = \frac{5}{2}^-$) are the only levels near 5.0 MeV having branches to the $\frac{5}{2}^+$ member of the ground state triplet and the $\frac{3}{2}^-$ level near 1.5 MeV. This analog identification is tentative because of the weakness of the observed transitions.

4.8. The levels at 4.71 and 4.78 MeV. We shall speculate on a possible analog identification for the 4.71 and 4.78 MeV states based upon the situation as it now stands following the discussion in the previous subsections. One of these states is presumably the analog of the 4.68 MeV state in ^{19}F ($J^\pi = \frac{5}{2}^-$) and it has been suggested [ref. [13])] that an undiscovered state exists near 4.7 MeV in ^{19}F (possibly one of the previously observed levels is a doublet). It would be unusual if the level structure of the more thoroughly studied nucleus, ^{19}F, were less known than that of ^{19}Ne, but an unresolved doublet is certainly possible. However, a cursory review of the reported level properties [3]) in this region of ^{19}F discloses no anomalous behavior which would suggest that one of the known levels is a doublet. The following alternative solution, makes equally interesting speculation: i.e., that the discrepancy is due not to a missing state in ^{19}F, but to an extraneous state in ^{19}Ne. Of the two ^{19}Ne levels not observed in this work, the 4.71 and 4.78 MeV levels, the most probable candidate is the level at 4.78 MeV which has only been reported by one group [9,11]). Support for this hypothesis is provided by Dehnhard *et al.* [14]) in a study of the reaction ^{19}F(^{3}He, t)^{19}Ne. In their study, this reaction was observed to unselectively populate various states in the final nucleus, with all states (except the 4.78 MeV state) in this region of excitation being easily visible and populated with strengths differing by less than an order of magnitude. At our suggestion, the triton spectra, recorded at numerous angles, were re-examined by Dehnhard specifically looking for the 4.78 MeV state and no indication of it was found .Without the 4.78 MeV state, the identification of the 4.68 MeV state in ^{19}Ne is suggested, not simply by default, but also from the study by Bingham *et al.* [11]) who found that in the reactions ^{16}O(^{6}Li, ^{3}He)^{19}F and ^{16}O(^{6}Li, t)^{19}Ne the 4.68 MeV state in ^{19}F and the 4.71 MeV state in ^{19}Ne were populated with similar cross sections. Thus, it appears likely that the 4.78 MeV state in ^{19}Ne is extraneous and that the 4.68 MeV state in ^{19}F is the analog of the 4.71 MeV state in ^{19}Ne, completing the identification of analog pairs up to 5.1 MeV excitation.

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References

1) L. A. Zaremba, Ph. D. thesis, University of Maryland, 1970
2) J. B. Marion, Nucl. Data **A4** (1968) 301
3) F. Ajzenberg-Selove, Nucl. Phys. **A190** (1972) 1
4) F. Ajzenberg-Selove, Nucl. Phys. **A152** (1970) 1
5) J. W. Olness, A. R. Poletti and E. K. Warburton, Phys. Rev. **161** (1967) 1131
6) J. M. Davidson, Ph. D. thesis, University of Maryland, 1973
7) K. Gul, B. H. Armitage and B. W. Hooten, Nucl. Phys. **A122** (1968) 81
8) M. W. Greene and E. B. Nelson, Phys. Rev. **153** (1967) 1068
9) J. D. Garrett, R. Middleton and H. T. Fortune, Phys. Rev. **C2** (1970) 1243
10) A. D. Panagioutou and H. E. Gove, Nucl. Phys. **A196** (1972) 145
11) H. G. Bingham, H. T. Fortune, J. D. Garrett and R. Middleton, Phys. Rev. Lett. **26** (1971) 1448
12) D. H. Wilkinson, in Nuclear spectroscopy, vol. B (Academic Press, New York, 1960)
13) H. G. Bingham, H. T. Fortune, J. D. Garrett and R. Middleton, Phys. Rev. **C7** (1973) 60
14) D. Dehnhard and H. Ohnuma, John H. Williams Laboratory, University of Minnesota, Annual report, 1971, unpublished;
D. Dehnhard, private communication