Nuclear Energy Levels of F^{19}, F^{21}, Ne^{22}, and Ne^{24}†

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A 16-in. radius, 180° double-focusing magnetic spectrometer was used to investigate the nuclear energy levels of F^{19}, F^{21}, Ne^{22}, and Ne^{24} by analysis of protons and alpha particles produced by (t,p) and (t,α) reactions with natural neon and with Ne^{22} gas targets. Between excitation energies of 2.8 and 6.5 Mev, new levels in F^{19} were found at 5.102, 5.539, 5.628, 5.937, and 6.169 Mev. Previously reported levels at 3.29, 4.48, and 4.95 Mev were not observed. Up to an excitation energy of 4.3 Mev in F^{21}, new levels were seen at 3.451, 3.509, 3.635, 3.977, 4.056, and 4.158 Mev, while the four previously known lower states at 0.285, 1.104, 1.743, and 2.047 Mev were confirmed. The mass of F^{21} was determined to be 21.006624±0.000011 amu (O^{16} standard); $(M-A)=6.168\pm0.010$ Mev. In Ne^{22} 38 excited states were observed up to an excitation of 9.4 Mev. Levels at 1.277, 3.343, and 4.473 Mev were confirmed, while a previously reported level at 4.9 Mev was not observed. Energy levels in Ne^{24}, up to an excitation energy of 6.4 Mev, were found at 1.986, 3.873, 3.962, 4.764, 4.886, 5.576, (5.641), and 6.030 Mev. The mass of Ne^{24} was determined to be 24.001238±0.000011 amu (O^{16} standard); $(M-A)=1.153\pm0.010$ Mev. Standard deviations in the values for the excitation energies vary from 0.015 to 0.025 Mev. Some representative cross sections are reported.

I. INTRODUCTION

THE present experiment is one in a series of experiments[1,2] undertaken to measure the masses and energy levels of light nuclei by analysis of the charged reaction products of triton-induced reactions. In particular, the (t,p) reaction introduces two neutrons into the target nucleus and allows an investigation of nuclei which are difficult to produce by any other means. An added advantage of (t,p) and (t,α) reactions is the large positive Q value, which falls in general into the range from 4 to 10 Mev.

The energy levels of F^{19}, F^{21}, Ne^{22}, and Ne^{24} were investigated by (t,p) and (t,α) reactions in gas targets of natural neon and of highly enriched Ne^{22}. Charged reaction products were studied with a high resolution double-focusing magnetic spectrometer. The nuclei studied here range from F^{19} which has been extensively investigated, through the poorly known nuclei F^{21} and Ne^{22}, to Ne^{24}, whose level structure was heretofore unknown. The masses of F^{21} and Ne^{24} were measured with a greater precision than had been attained previously. A preliminary report of the energy levels of F^{21} and Ne^{24} has been made.[3] The present experimental situation for each of these nuclei will be discussed in the sections dealing with the results for the individual nuclei.

II. EXPERIMENTAL

A. Equipment

The experimental procedure in the present investigation has been described in previous papers.[2,4] Briefly, gas targets of natural spectroscopic-grade neon or of neon enriched[5] to 99.9% Ne^{22} were bombarded with tritons accelerated to a maximum energy of 2.6 Mev with an electrostatic accelerator. Charged reaction products were analyzed at a laboratory angle of 30° with a 16-in. radius, 180° double-focusing magnetic spectrometer.

The resolution of the system was such that proton and alpha-particle groups at energies of 2 Mev displayed full widths at half maximum of 30 and 50 kev, respectively. At 6 Mev, widths of both proton and alpha-particle groups were 48 kev. Widths greater than these values could be attributed either to energy levels with significant intrinsic widths or to unresolved groups of levels. With several exceptions, all particle groups which appeared abnormally broad were at least partially resolved into two groups. Experimental factors therefore set an upper limit, estimated at 30 kev, on the intrinsic widths of most levels observed. The exceptions were small groups for which counting statistics were too poor to differentiate between intrinsically broad levels and closely spaced doublets.

Mass-spectrometric analysis of the neon target gases showed the presence of small amounts (a few tenths of 1 at. % or less) of hydrogen, carbon, nitrogen, oxygen, and argon as contaminants. The isotopic abundance of the neon isotopes in the natural neon was in good agreement with accepted values: Ne^{20}—90.5%, Ne^{21}—0.28%, Ne^{22}—9.2%. The isotopic composition of the enriched neon was Ne^{20}—0.012%, Ne^{21}—0.025%, Ne^{22}—99.96%.

Particle groups not associated with the reactions of interest were due to target contaminants or to beam contaminants [H_3^+, HD^+, and $(He^3)^+$]. Identification of groups from triton reactions with contaminants in the target gases was possible since spectra have been taken with methane, nitrogen, oxygen, and argon targets under similar conditions. Groups due to scattering and reactions of beam contaminants could be identified by changing the rf ion-source operating conditions, which virtually eliminated the beam contaminants compared to normal conditions.

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[1] N. Jarmie, Phys. Rev. **104**, 1683 (1956).
[2] N. Jarmie and M. G. Silbert, Phys. Rev. **120**, 914 (1960).
[3] *Proceedings of the International Conference on Nuclear Structure, Kingston, Canada*, edited by D. A. Bromley and E. W. Vogt (University of Toronto Press, Toronto, Canada, 1960), p. 967.
[4] N. Jarmie and R. C. Allen, Phys. Rev. **111**, 1121 (1958).
[5] The 99.9% Ne^{22} was purchased from the Physikalisch-Chemisches Institut der Universität Zürich, Zürich, Switzerland, through the kind cooperation of the director, Professor K. Clusius.

TABLE I. List of reactions used for energy calibration. Reaction Q values were calculated from masses of reference 6; excitation energies were taken from reference 7.

Reaction	Residual excited state (Mev)	Calculated Q value (Mev)
$H(t,p)T$		0, elastic scattering
$C^{12}(t,p)C^{14}$	g.s.	4.640±0.001
$C^{12}(t,\alpha)B^{11}$	g.s.	3.857±0.001
$O^{16}(t,p)O^{18}$	g.s.	3.706±0.001
	1.980±0.004	1.726±0.004
$O^{16}(t,\alpha)N^{15}$	g.s.	7.687±0.001
	6.328±0.004	1.359±0.004
	7.307±0.004	0.380±0.004
$Ne^{20}(t,\alpha)F^{19}$	1.347±0.003	5.622±0.003
	1.460±0.003	5.509±0.003
	1.556±0.003	5.413±0.003

B. Energy Determination and Errors

Measurements in this experiment were taken in the same way as in the previous experiment with oxygen targets,[2] except that energy determination was made on the basis of the spectrometer magnet current. The choice of this method was dictated by the large number of levels to be measured since use of the fluxmeter was considerably more time consuming while it did not greatly improve the accuracy of the energy determination. The energy scale of the spectrometer was determined by the positions of particle groups corresponding to reactions whose Q values are presumably known to within several kev. This method of energy calibration had the advantage of minimizing systematic errors such as those introduced by an imperfect knowledge of the energy losses in the target gases. Furthermore, the calibration peaks could be observed in the spectra of unknowns since carbon and oxygen were easily introduced in the neon target gases as CO_2, or were present as contaminants. The method had the disadvantage of depending on Q values calculated from atomic masses which are not always as well known as assumed. A check on the calculated Q values was afforded by the consistency of the energy scale determined by several different reactions and at several triton bombarding energies.

The reactions used for energy calibration are presented in Table I together with Q values calculated from the atomic mass table of Everling, König, Mattauch, and Wapstra.[6] Excitation energies of excited

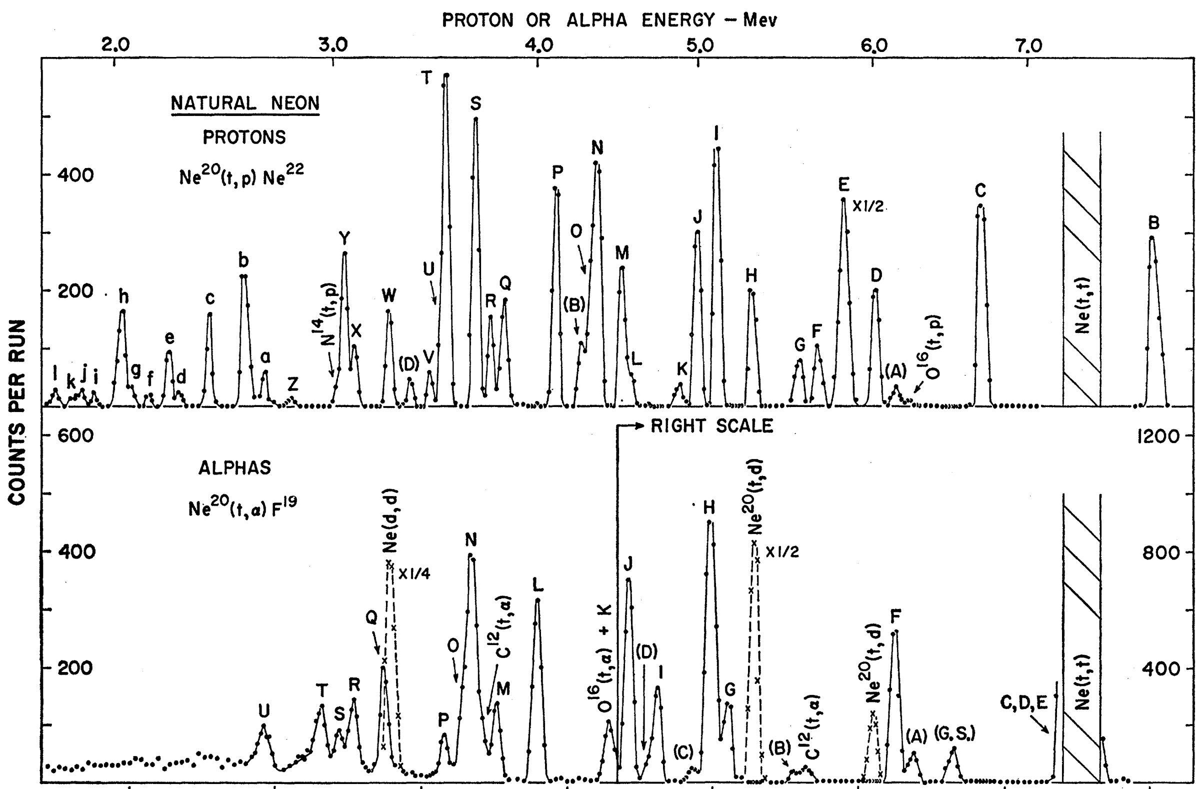

FIG. 1. Spectra of protons and alpha particles at 30° (lab) from the bombardment of a natural neon target with 2.62-Mev tritons. The spectrometer momentum resolution was 196. Letters refer to groups associated with reactions in Ne^{20}; letters in parentheses refer to reactions in Ne^{22}. Deuteron groups are distinguished by crosses and dashed lines.

[6] F. Everling, L. A. König, J. H. E. Mattauch, and A. H. Wapstra, Nuclear Phys. 18, 529 (1960).

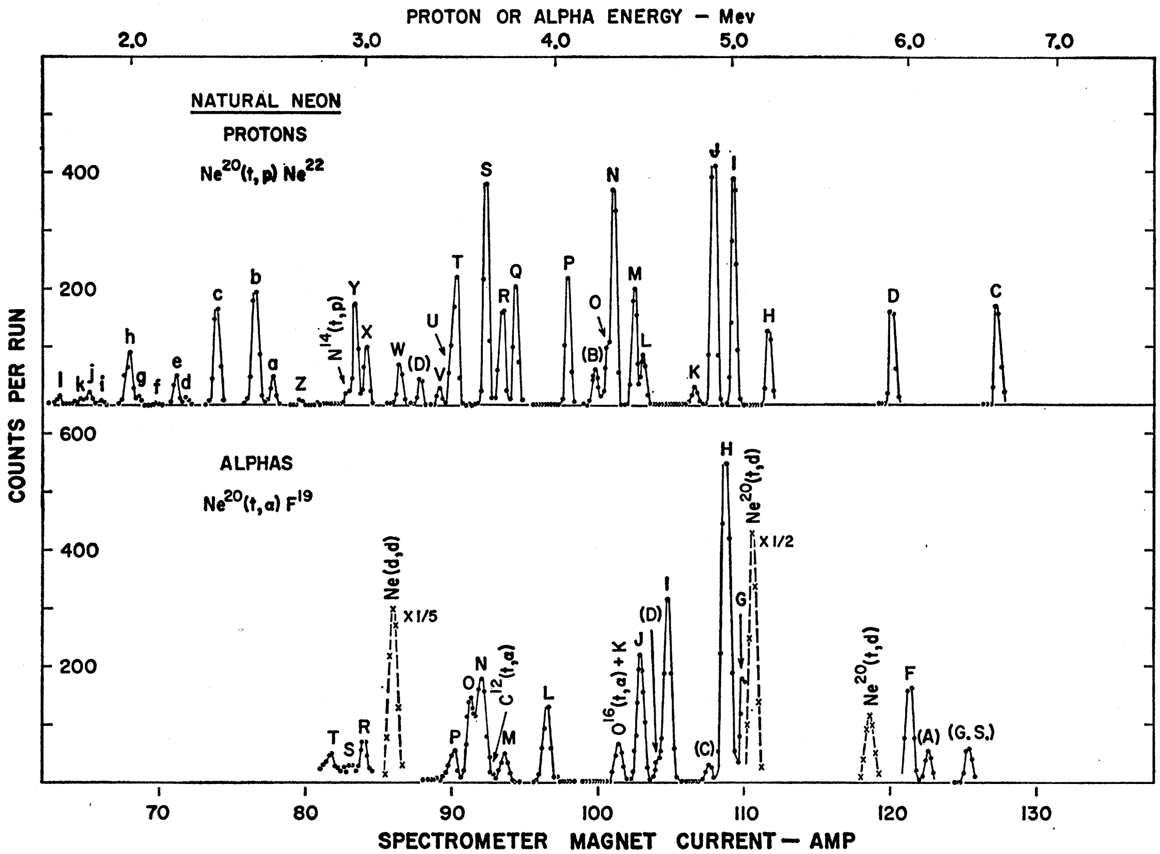

FIG. 2. Spectra of protons and alpha particles at 30° (lab) from the bombardment of a natural neon target with 2.52-Mev tritons. The spectrometer momentum resolution was 354. Letters refer to groups associated with reactions in Ne^{20}; letters in parentheses refer to reactions in Ne^{22}. Deuteron groups are distinguished by crosses and dashed lines.

states were taken from the compilations of Ajzenberg-Selove and Lauritsen.[7]

The procedure for obtaining excitation energies of levels in F^{19}, F^{21}, Ne^{22}, and Ne^{24} was to observe the spectrometer field coil current corresponding to the peak of a particle group, calculate the group energy from the energy scale established by calibration peaks, calculate a Q value, and subtract this value from the ground state Q value determined from atomic mass tables[6] (F^{19}, Ne^{22}) or measured in this experiment (F^{21}, Ne^{24}).

The energy of a particle group was uncertain to some ± 7 kev (depending on the number of determinations) because of random errors in its measurement and uncertain to ± 8 kev because of errors in the energy scale, so that an over-all error of ± 11 kev can be assigned. Systematic errors, except in the calibration Q values, would appear in the calibrations in a manner similar to that in the unknowns and would be largely compensated. Taking into account possible systematic errors, a conservative standard deviation of ± 15 kev has been assigned to the Q values of well-determined groups.

III. RESULTS AND DISCUSSION

A. General

Representative spectra obtained in the present experiment are illustrated in Figs. 1 to 3. The convention has been adopted of indicating groups attributed to reactions with Ne^{20} by letters alone; groups associated with reactions with Ne^{22} are designated by letters in parentheses. Estimates of the upper limits on the statistical counting errors for the experimental points can be made by noting that the ordinates in the figures are the actual number of counts per run. Additional data, taken for various corroborative purposes, have not been presented here. For instance, the area under the triton scattering peak was uncovered by reducing the incident triton energy to 2.0 Mev. Since the energy scales for tritons and deuterons are different from that for protons and alpha particles, triton and deuteron peaks could be shifted relative to proton and alpha peaks by changing the bombarding energy. This served as a positive identification for deuterons which were difficult to distinguish from alphas on the basis of pulse

[7] F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. **11**, 1 (1959) and *Landolt-Börnstein Tables, Supplementary Volume on Nuclear Physics* (Springer-Verlag, Berlin, Germany, 1961), 6th ed.

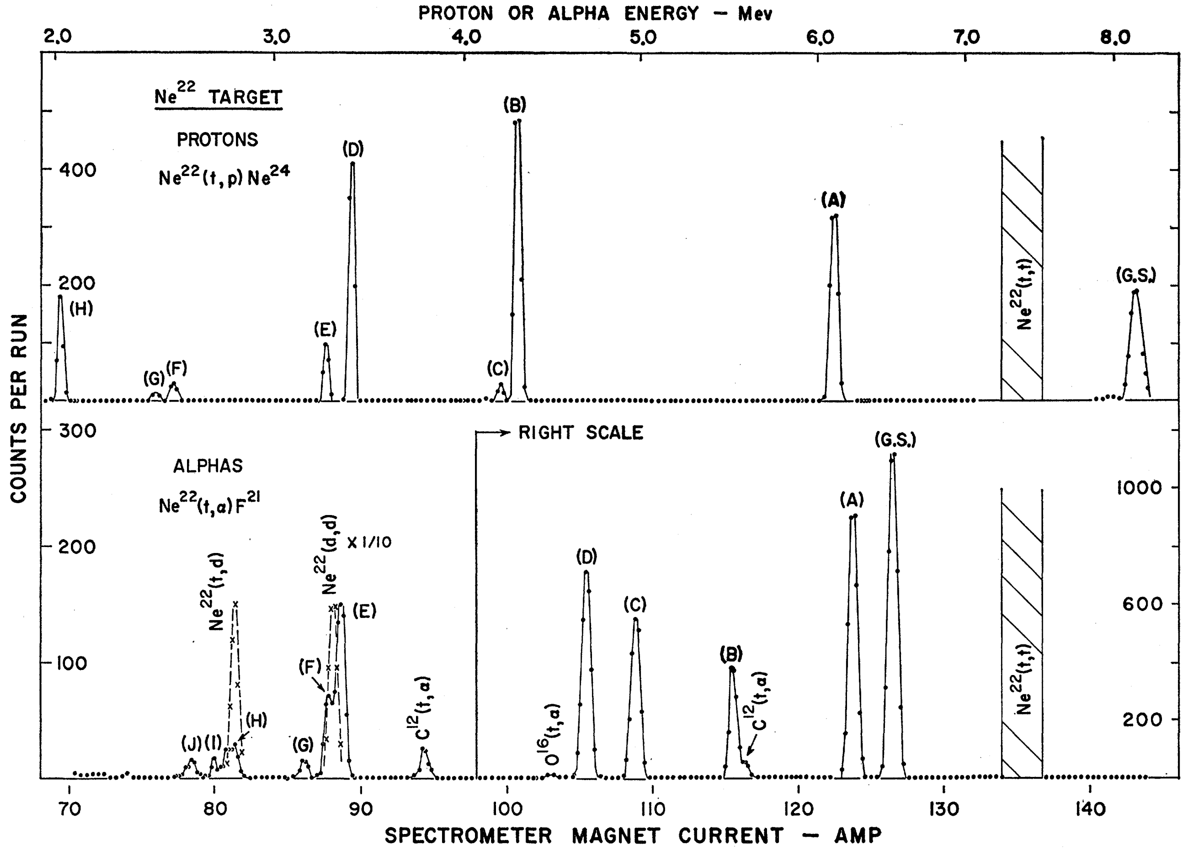

FIG. 3. Spectra of protons and alpha particles at 30° (lab) from the bombardment of a 99.9% Ne^{22} target with 2.62-Mev tritons. The spectrometer momentum resolution was 196. Deuteron groups are distinguished by crosses and dashed lines.

height alone. Deuteron groups have been included in the alpha spectra in Figs. 1 to 3.

Additional high-resolution runs were made on several of the closely spaced levels which were poorly resolved, to obtain sufficient information for energy determinations. Examples of the resolution of closely spaced levels with this equipment are illustrated in Fig. 3 of reference 2.

Some representative cross sections for triton-induced reactions in Ne^{22} are presented in Table II. If estimates of other cross sections are made on the basis of Figs. 1 to 3, it should be noted that the cross sections are proportional to the areas of peaks divided by the spectrometer current. In regions free from the alpha continuum and not obscured by contaminant peaks, an upper limit on the cross sections of possible missed levels is estimated to be 0.01 mb/sr.

B. F^{19}

Typical alpha-particle spectra obtained with tritons incident on a natural neon target are shown in Figs. 1 and 2. These spectra represent data obtained at two triton bombarding energies with two values of the spectrometer resolution. The energy levels of F^{19} measured in the present experiment are given in Table III, together with the results of previous experiments. Previous values have been adjusted, where appropriate, to correct for changes brought about by the most recent least-squares adjustment of atomic masses by Everling *et al.*[6]

The effective limit in excitation energy searched was 6.6 Mev, corresponding to an alpha energy of 2.6 Mev. Emission of alpha particles of energy less than about 3 Mev was inhibited by the Coulomb barrier of the compound nucleus. Below about 78 amp, small peaks would be hidden by the alpha continuum from the reaction $Ne^{20}(t,2\alpha)N^{15}$. This continuum, which was not energetically possible with the Ne^{22} target, is evident up to about 90 amp in Fig. 1.

Two deuteron groups (121 and 113 amp, Fig. 1) were attributed to $Ne^{20}(t,d)Ne^{21}$ (ground state and first excited state). The deuteron scattering peak at 88 amp has its origin in the small HD^+ component of the beam.

Groups C, D, and E were masked by the triton scattering peak at $E_t=2.6$ Mev. They were seen clearly at $E_t=2.0$ Mev and were used as calibration points for the energy scale. The peak marked $O^{16}(t,\alpha)+K$ corresponds to the position where alpha groups to the

TABLE II. Representative differential cross sections for (t,p) and (t,α) reactions in Ne^{22} at 30° (lab). Absolute standard deviations in the cross sections are ±30%.

Reaction	Triton energy (Mev)	Cross section (mb/sr)
$Ne^{22}(t,p)Ne^{24}$ (g.s.)	1.76	0.54
	1.80	0.45
	1.98	0.03
	2.52	0.40
	2.62	0.41
$Ne^{22}(t,p)Ne^{24}$ (1st exc. st.)	1.76	0.11
	1.80	0.09
	2.52	0.43
	2.62	0.58
$Ne^{22}(t,\alpha)F^{21}$ (g.s.)	1.76	0.38
	1.80	0.48
	1.98	0.89
	2.52	1.74
	2.62	2.17
$Ne^{22}(t,\alpha)F^{21}$ (1st exc. st.)	1.76	0.25
	1.80	0.19
	2.52	1.60
	2.62	1.77

first and second excited states (5.276 and 5.305 Mev) of N^{15} would be expected. One at. % of oxygen in the target would be required to yield the observed group, a level of contamination considerably higher than analysis of the gas would indicate. It seems probable that the group was at least partly due to a known level, K, in F^{19}, but energy determination of this level is difficult.

Fluorine-19 has been studied extensively, in part because of the great theoretical interest in mass-19 nuclei. Calculations on F^{19} energy levels have been carried out by a number of investigators.[8] The following discussion will be limited to the region of excitation above the 1.56-Mev level. This region has been investigated by several experimental groups with the reactions $F^{19}(p,p')F^{19*}$, $O^{18}(d,n)F^{19*}$, $N^{15}(\alpha,\alpha)N^{15}$, and $N^{15}(\alpha,\gamma)F^{19}$ (Table III).

In chronological order: Arthur, Allen, Bender, Hausman, and McDole[9] investigated protons that were inelastically scattered from thin fluoride targets and analyzed by a magnetic spectrometer. Good resolution was attained although the incident proton beam had a spread of 0.04 Mev. Seale[10] observed the neutron spectrum from $O^{18}(d,n)F^{19}$ with nuclear plates. Resolution was fair with considerable overlap of levels. Harlow, Marion, Chapman, and Bonner[11] used a neutron threshold technique with $O^{18}(d,n)F^{19*}$, but observed only two levels in the region of excitation from 6.1 to 9.8 Mev in F^{19}. Squires, Bockelman, and Buechner[12] analyzed protons inelastically scattered from thin fluoride targets with a high-resolution magnetic spectrograph. Their data unfortunately extend only to an

TABLE III. Energy levels of F^{19}. See text for references to the various experiments.

Group	Present experiment	Ajzenberg-Selove and Lauritsen	Arthur *et al.*	Seale	Squires *et al.*	Singh	Freeman	Hossain and Kamal	Price	Smotrich
F	2.794±0.015	2.793±0.007	2.82±0.030	2.78±0.100	2.784±0.008	2.7	2.79±0.015	2.83±0.020		
	...	...				3.29				
G	3.917±0.015	3.912±0.010	3.94±0.030	3.88±0.100	3.912±0.010	3.7		3.92±0.040		
H	4.032±0.015	{4.002±0.010			4.002±0.010					
		4.036±0.010}	4.06±0.030		4.036±0.010			4.06±0.050		
I	4.385±0.015	(4.41)	4.41±0.030							
	...	(4.48)	4.48±0.030	4.5 ±0.100		4.5				
J	4.563±0.015	4.576±0.017	4.59±0.030			4.63		4.57±0.020		
K	(4.690±0.040)	4.76 ±0.026	4.76±0.030	4.8 ±0.100		4.8		4.76±0.050		
	...	(4.95)						(4.95±0.020)		
L	5.102±0.015	...		5.2 ±0.100						
M	5.343±0.015	5.339±0.004				5.3		5.27±0.020	5.339±0.005	
N	5.481±0.015	{5.474±0.003							5.474±0.003	
		5.499±0.003}		5.5 ±0.100		5.53		5.53±0.030	5.498±0.003	5.488±0.010
O	5.539±0.015	...								
					Butler and Holmgren		Harlow *et al.*			
P	5.628±0.015	...								
Q	5.937±0.020	...								
R	6.092±0.015	{6.074±0.008			6.079±0.008			6.07±0.020		6.069±0.010
		6.085±0.010}			(6.10)					6.085±0.010
S	6.169±0.020	...								
T	6.247±0.025	{6.241±0.008			6.241±0.008	6.24	6.215±0.015			6.242±0.010
		6.287±0.010}			6.293±0.010					6.281±0.010
	...	6.329±0.010								6.329±0.010
	...	6.43 ±0.010								6.43 ±0.010
U	6.501±0.025	{6.527±0.010				6.50		(6.50±0.090)		6.527±0.010
		6.554±0.010}								6.554±0.010

[8] See reference 7 for a list of theoretical papers on F^{19}.
[9] J. C. Arthur, A. J. Allen, R. S. Bender, H. J. Hausman, and C. J. McDole, Phys. Rev. **88**, 1291 (1952).
[10] R. L. Seale, Phys. Rev. **92**, 389 (1953).
[11] M. V. Harlow, J. B. Marion, R. A. Chapman, and T. W. Bonner, Phys. Rev. **101**, 214 (1956).
[12] G. L. Squires, C. K. Bockelman, and W. W. Buechner, Phys. Rev. **104**, 413 (1956).

excitation of 4.04 Mev. Singh[13] investigated $O^{18}(d,n)F^{19}$ with nuclear plates.

Freeman[14] observed the gamma rays from $F^{19}(n,n')F^{19*}$ and obtained a value for the 2.79-Mev state. Hossain and Kamal[15] analyzed nuclear plates which had been exposed to protons scattered from a gaseous fluoride target. Resolution was fair and levels were measured up to 6.5-Mev excitation. Price[16] used $N^{15}(\alpha,\gamma)F^{19}$ and observed steps in the thick-target yield of gamma rays. He detected three levels in F^{19} near 5.4-Mev excitation. Butler and Holmgren[17] used a gamma threshold technique with $O^{18}(d,n\gamma)F^{19}$. They reported three levels in F^{19}. Finally, Smotrich[18] observed resonances in the elastic scattering of alpha particles by N^{15}. He was able to assign spins, parities, and widths to a number of levels.

Summarizing the experimental evidence, including the present experiment, the following levels in F^{19} now seem to be well established in the region of interest: 2.793, 3.912, 4.002, 4.036, 4.385, 4.563, 4.76, 5.102*, 5.339, 5.474, 5.499, 5.539*, 5.628*, 5.937*, 6.074, 6.085, 6.169*, 6.241, 6.287, 6.43, 6.329, 6.527, and 6.554 Mev. Those marked by an asterisk are previously unreported levels observed in the present experiment. The criterion for inclusion in this list was observation in at least one good-resolution experiment. Wherever a previously well-determined level was resolved in this experiment, the agreement in energy was excellent.

Groups *H*, *N*, *R*, *T*, and *U* correspond to previously reported closely spaced doublets which could not be resolved in this experiment. With the exception of *U*, these groups agreed well with an average of the energy values given[7] for each doublet. Group *U* was centered at 6.501 Mev and lay somewhat below the levels reported by Smotrich at 6.527 and 6.554 Mev. It appeared to consist of two poorly resolved groups at about 6.479 and 6.508 Mev.

The possibility exists that groups *N* and *O* correspond to the two levels reported by Price at 5.474 and 5.498 Mev, although the separation reported by him was 25±4 kev as compared to 58±10 kev for *N* and *O*. An alternate, more probable conclusion is that *N* corresponds to the two levels given by Price, while *O* is a new level.

Three levels, considered possible F^{19} levels on the basis of previous reports, were not seen in the present experiment; those at 3.29, 4.48, and 4.95 Mev. The level reported by Singh at 3.29 Mev has not been observed in any other experiment. It would correspond to 117 amp in Fig. 1 and the possibility of a small group hidden by (*B*) or $C^{12}(t,\alpha)$ cannot be eliminated. A level was reported by Arthur *et al.* at 4.48±0.03 Mev. Both Seale and Singh reported levels at 4.5 Mev, although these may correspond to the 4.57-Mev level or possibly the 4.39-Mev level, or both. In the present experiment, 4.48-Mev excitation would correspond to 104 amp (Fig. 2) where an F^{21} group, (*D*), 40 counts high, was expected on the basis of runs with an Ne^{22} target. A poorly resolved group of the expected size was observed and a group corresponding to an F^{19} level at 4.48 Mev would need to have a cross section less than 1/20 that of the 4.385-Mev group. Hossain and Kamal reported a possible energy level at 4.95±0.02 Mev, the only report of such a level. A group corresponding to this excitation would appear at 100 and 98 amp in Figs. 1 and 2, respectively. This region is quite clean and no level in the vicinity of 4.95 Mev is indicated by the present experiment.

All four experiments which covered this region previously indicated a level near 4.76 Mev. As discussed above, the group labeled $O^{16}(t,\alpha)+K$ probably corresponds in part to this state. Present evidence is that the level is somewhat lower in excitation than formerly supposed. A value of 4.690±0.040 Mev has been assigned. The disagreement is not serious since the previous average value was uncertain by ±26 kev.

Alpha groups corresponding to excitation energies above about 6 Mev in F^{19} became progressively smaller and the alpha continuum became appreciable so that counting statistics were relatively poor and peaks were not as well defined as at lower excitations. Group *T* corresponds to the level reported both by Smotrich and by Butler and Holmgren at 6.24 Mev. The value 6.215 Mev obtained by Harlow *et al.* probably corresponds to the same state. Singh also reported a level at 6.24 Mev. There are indications of small, unresolved groups on the low-energy side of *T* which correspond to the level at 6.29 Mev reported by Smotrich and by Butler and Holmgren and to the level at 6.329 Mev reported by Smotrich.

A broad level ($\Gamma=358$ kev) was reported by Smotrich at 6.43 Mev. This would correspond to 81 amp in Fig. 1, in the minimum between peaks *T* and *U*. Although there is no evidence for such a level in the present experiment the alpha continuum might mask a low, broad group.

C. F^{21}

A typical alpha-particle spectrum observed from the reaction $Ne^{22}(t,\alpha)F^{21}$ with a highly enriched Ne^{22} target is presented in Fig. 3. The mass and energy levels of F^{21} up to 4.3-Mev excitation derived in the present experiment are given in Table IV, together with the values obtained by Jarmie[1] from a study of $F^{19}(t,p)F^{21}$.

The only contaminant groups identified in the alpha spectrum from the Ne^{22} target were those due to $C^{12}(t,\alpha)$ reactions leading to the ground and first excited states

[13] R. G. Singh, thesis, University of Florida, 1956 (unpublished) and Dissertation Abstr. **17**, 386 (1957).
[14] J. M. Freeman, Phil. Mag. **2**, 628 (1957).
[15] A. Hossain and A. N. Kamal, Phys. Rev. **108**, 390 (1957).
[16] P. C. Price, Proc. Phys. Soc. (London) **70A**, 661 (1957).
[17] J. W. Butler and H. D. Holmgren, Phys. Rev. **112**, 461 (1958).
[18] H. H. Smotrich, Columbia University Report CU-188, 1959 (unpublished); H. Smotrich, K. W. Jones, L. C. McDermott, and R. Benenson, Bull. Am. Phys. Soc. **4**, 359 (1959).

of B^{11}. The ground state group from $Ne^{22}(t,d)Ne^{23}$ was observed as was the deuteron elastic scattering peak.

A series of measurements was made on the ground-state group in order to get a good determination of the mass of F^{21}. The most precise of these was a run with a target of 25% (by volume) CO_2 and 75% Ne^{22} so that comparison could be made to the nearby peaks from $O^{16}(t,p)O^{18}$ (g.s.) and $C^{12}(t,p)C^{14}$ (g.s.). The results of these various measurements were quite consistent and yielded an average Q value for $Ne^{22}(t,\alpha)F^{21}$ of 4.548 ± 0.010 Mev. This leads to a mass for F^{21} of 21.006624 ± 0.000011 amu (O^{16} standard) and a mass defect $(M-A)$ of 6.168 ± 0.010 Mev.

There have been few experiments on the mass and energy levels of F^{21}. The first data were from the work of Bigham, Allen, and Almqvist[19] who studied the reaction $F^{19}(t,p)F^{21}$ with nuclear emulsion and NaI crystal techniques. They obtained a mass defect of 6.37 ± 0.1 Mev and energy levels at 0.89 ± 0.08 Mev and possibly at 3.34 ± 0.10 and 4.01 ± 0.10 Mev. It seems possible that Bigham *et al.* mistook the level at 0.27 Mev for the ground state. This would account for the 0.2-Mev discrepancy, both in F^{21} mass and in the energy of the excited state at 1.1 Mev, between their results and the results of Jarmie and of the present experiment. The $F^{19}(t,p)F^{21}$ reaction was used by Jarmie[1] at this laboratory with essentially the same apparatus as in the present experiment. Thin fluoride targets were bombarded with 1.8-Mev tritons and emerging protons were analyzed with the 16-in. radius, double-focusing magnetic spectrometer. The energy levels reported by Jarmie are compared to the present results in Table IV. His value for the mass of F^{21} is in good agreement with the present results.

Peaks (A) through (D) correspond to the four levels found by Jarmie and are in good agreement with his values. Peaks (E) through (J) represent six previously unknown levels in F^{21}. They are grouped roughly into two triplets which probably correspond to the possible levels reported by Bigham *et al.* at 3.34 and 4.01 Mev. Groups (E) and (F) were only partly resolved. The alphas were clearly separated from the deuterons, both at 81 and 88 amp. Group (H) was abnormally broad and flat-topped. Since a level at this excitation would be heavy-particle stable and therefore would not be this broad, (H) probably represents an unresolved doublet of less than 40-kev separation. No alpha peaks were observed below 76 amp; the limit of excitation energy searched is estimated to be 4.3 Mev.

TABLE IV. Energy levels of F^{21}.

Group	Present experiment Excitation energy (Mev)	Jarmie (1956)[a] Excitation energy (Mev)
(g.s.)	0; $(M-A)=6.168\pm0.010$	0; $(M-A)=6.191\pm0.025$
(A)	0.285 ± 0.018	0.269 ± 0.040
(B)	1.104 ± 0.018	1.087 ± 0.040
(C)	1.743 ± 0.018	1.694 ± 0.040
(D)	2.047 ± 0.018	2.036 ± 0.040
(E)	3.451 ± 0.018	
(F)	3.509 ± 0.025	
(G)	3.635 ± 0.020	
(H)	3.977 ± 0.025	
(I)	4.056 ± 0.025	
(J)	4.158 ± 0.025	

[a] N. Jarmie, Phys. Rev. **104**, 1683 (1956).

D. Ne^{22}

Figures 1 and 2 show proton spectra obtained from the reaction $Ne^{20}(t,p)Ne^{22}$ with natural neon targets. The energy levels of Ne^{22} up to an excitation of 9.4 Mev are given in Table V together with the results of Martin, Sampson, and Miller.[20]

TABLE V. Energy levels of Ne^{22}.

Group	Present experiment Excitation energy (Mev)	Martin, Sampson, Miller[a] Excitation energy (Mev)
g.s.	0	0
A	[1.277 ± 0.004][b]	1.28 ± 0.03
B	3.343 ± 0.015	3.37 ± 0.03
C	4.473 ± 0.015	4.52 ± 0.03
D	5.139 ± 0.015	5.18 ± 0.05
E	5.340 ± 0.015	
F	5.520 ± 0.015	
G	5.633 ± 0.015	5.67 ± 0.03
H	5.917 ± 0.015	
I	6.117 ± 0.015	
J	6.242 ± 0.015	
K	6.349 ± 0.015	6.41 ± 0.03
L	6.647 ± 0.015	
M	6.696 ± 0.015	
N	6.823 ± 0.015	
O	6.860 ± 0.025	6.88 ± 0.03
P	7.047 ± 0.015	
Q	7.331 ± 0.015	
R	7.402 ± 0.015	
S	7.484 ± 0.015	7.49 ± 0.03
T	7.633 ± 0.015	
U	7.663 ± 0.020	
V	7.720 ± 0.015	
W	7.913 ± 0.015	
X	8.071 ± 0.015	
Y	8.122 ± 0.015	
Z	8.368 ± 0.015	
a	8.488 ± 0.015	
b	8.575 ± 0.015	
c	8.724 ± 0.015	
d	8.844 ± 0.015	
e	8.890 ± 0.015	
f	8.970 ± 0.015	
g	9.034 ± 0.020	
h	9.069 ± 0.015	
i	9.174 ± 0.020	
j	9.215 ± 0.020	
k	9.242 ± 0.020	
l	9.316 ± 0.015	

[a] H. J. Martin, M. B. Sampson, and D. W. Miller, Phys. Rev. **121**, 877 (1961).
[b] Observed but not measured; value from reference 7.

[19] C. B. Bigham, K. W. Allen, and E. Almqvist, Phys. Rev. **99**, 631A (1955).

[20] H. J. Martin, M. B. Sampson, and D. W. Miller, Phys. Rev. **121**, 877 (1961).

Groups corresponding to the ground and first excited states of Ne^{22} were observed but no attempt was made to determine their energies accurately since they are presumably well known and were too high in energy for an accurate measurement by the present means. Thirty-seven additional levels in Ne^{22} were seen in the present experiment.

The first few energy levels in Ne^{22} were fairly well determined in the past, principally by the reactions $F^{19}(\alpha,p)Ne^{22}$, $Ne^{21}(d,p)Ne^{22}$, and $Na^{23}(\gamma,p)Ne^{22}$, and by inelastic scattering of protons and alphas from Ne^{22}. The first excited state at 1.277 Mev was also studied following the β decay of Na^{22} which proceeds nearly completely to this level.

Older reports apparently established levels at 3.35 and 4.9 Mev and possibly two others at 5.4 and 5.7 Mev, although conflicting results have been obtained. The region between 5.7 and 11.5 Mev was unexplored. Above 11.5 Mev, levels have been observed as resonances in $O^{18}(\alpha,n)Ne^{21}$ and $F^{19}(t,\alpha)O^{18}$. Recently, Martin *et al.*[20] measured levels up to 7.5 Mev in Ne^{22} by analyzing protons from $F^{19}(\alpha,p)Ne^{22}$ with a magnetic spectrometer. They bombarded a thin fluoride target with 21-Mev alpha particles from a cyclotron and observed eight excited states (Table IV). Their resolution was considerably poorer than that in the present experiment. The values of Martin *et al.* appear to lie consistently some 40 kev above the present results.

The present experiment gives the most accurate value to date for the second excited state as 3.343 $\pm$0.015 Mev, in good agreement with the value 3.37$\pm$0.03 Mev obtained by Martin *et al.* Both that experiment and the present experiment agree on a value of about 4.5 Mev for the next excited state, in contradiction to the previously accepted value[7] of 4.9 Mev. This value would correspond to 124 amp in Fig. 1. The area between D and C was carefully searched for a possible level. Group (A) was in excellent agreement both in position and size with what would be expected from the 9% of Ne^{22} in the natural neon target. The small group labeled $O^{16}(t,p)$ was attributed to the reaction leading to the ground state of O^{18} and would correspond to 0.2 at. % O^{16} in the target, in reasonable agreement with the mass-spectrometric analysis of the gas. The present experiment yields no evidence for a state in Ne^{22} near 4.9 Mev.

Assignment of the value 4.9 Mev was made on the basis of two experiments: by Foster, Stanford, and Lee[21] and by Seidlitz, Blueler, and Tendam.[22] On the other hand, Ophel and Wright[23] reported a value of 4.4$\pm$0.1 Mev obtained by study of $Na^{23}(\gamma,p)Ne^{22}$. They also reported the levels at 5.4 and 5.7 Mev. Ophel and Wright discussed the assignment of 4.9 Mev made by Foster *et al.* and concluded that the data was ambiguous. The position of the third excited state now seems well established at 4.5 Mev.

[21] B. P. Foster, G. S. Stanford, and L. L. Lee, Jr., Phys. Rev. **93**, 1069 (1954).
[22] L. Seidlitz, E. Bleuler, and D. J. Tendam, Bull. Am. Phys. Soc. **1**, 29 (1956).
[23] T. R. Ophel and I. F. Wright, Proc. Phys. Soc. (London) **71A**, 389 (1958).

TABLE VI. Energy levels of Ne^{24}.

Group	Present experiment Excitation energy (Mev)
(g.s.)	0; $(M-A)=1.153\pm0.010$
(A)	1.986$\pm$0.018
(B)	3.873$\pm$0.018
(C)	3.962$\pm$0.018
(D)	4.764$\pm$0.018
(E)	4.886$\pm$0.018
(F)	5.576$\pm$0.018
(G)	(5.641$\pm$0.025)
(H)	6.030$\pm$0.018

E. Ne^{24}

Figure 3 illustrates a typical proton spectrum from the reaction $Ne^{22}(t,p)Ne^{24}$ with a highly enriched Ne^{22} target. The energy levels of Ne^{24}, up to an excitation energy of 6.4 Mev, are presented in Table VI. Neon-24, with 10 protons and 14 neutrons, is an isobaric spin $T=2$ nucleus.

The energy of the ground state group was determined by comparison to the groups from $C^{12}(t,p)C^{14}$ (g.s.) and $O^{16}(t,\alpha)N^{15}$ (g.s.) with a target of 25% (by volume) CO_2 and 75% Ne^{22}. This led to a Q value for $Ne^{22}(t,p)Ne^{24}$ of 5.587$\pm$0.010 Mev and a mass for Ne^{24} of 24.001238 $\pm$0.000011 amu (O^{16} standard). The mass defect $(M-A)$ is calculated to be 1.153$\pm$0.010 Mev. The only previous measurement of the mass of Ne^{24} was by Dropesky and Schardt[24] who analyzed the decay of Ne^{24} produced by $Ne^{22}(t,p)Ne^{24}$. From the β-decay end points, gamma energies, and the mass of Na^{24} they derived a mass for Ne^{24}. If the more recent value of the Na^{24} mass given by Everling *et al.* is combined with the β-decay results, a mass for Ne^{24} of 24.001225 $\pm$0.000038 amu is obtained. This is in excellent agreement with the present value.

No measurement of the energy level scheme for Ne^{24} had been carried out before the present experiment. Seven definite levels and one probable level were found up to an excitation energy of 6.4 Mev. Group (G) is only considered a probable Ne^{24} level because of its small size, although the background is negligible in this region and the peak was observed on each run.

[24] B. J. Dropesky and A. W. Schardt, Phys. Rev. **102**, 426 (1956).