^{18}N and ^{22}F Ground States, ^{22}F Excited States, and $T=2$ Analogs in ^{22}Ne†

RICHARD H. STOKES AND P. G. YOUNG
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico

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Energy spectra of ^{3}He ions from the ^{18}O$(t, ^3$He$)^{18}$N and the ^{22}Ne$(t, ^3$He$)^{22}$F reactions have been measured for a triton bombarding energy of 22 MeV. A proportional ΔE detector and a silicon E detector were used to identify and measure the energy of the ^{3}He ions. From Q-value determinations, ground-state mass excesses (^{12}C=0) were found to be 13.274±0.030 MeV for ^{18}N and 2.828±0.030 MeV for ^{22}F. The ^{22}F mass value is 1.67 MeV lower than the only previously reported value. Other groups in the spectra correspond to the first observation of excited states in ^{22}F. Excitation-energy values for these six excited states are 0.66, 1.36, 1.57, 1.97, 2.54, and 2.91 MeV. Also, spectra from the (p, p'), (d, d'), and (t, t') reactions were measured with a ^{22}Ne target to search for $T=2$ analogs to ^{22}F states. Groups which appeared only in the ^{22}Ne(p, p') and ^{22}Ne(t, t') spectra have Coulomb-energy shifts and widths which suggest that they are analogs to the ground, second, third, and fourth excited states of ^{22}F. Based on the measured values of the ^{18}N and ^{22}F ground-state masses and the systematics of pairing energy, estimates are made for the masses of the unreported nuclei ^{22}Al, ^{19}N, ^{21}O, and ^{23}F. The last three nuclei are predicted to be stable against neutron decay, whereas ^{22}Al is estimated to be near the limit of proton stability.

INTRODUCTION

THERE has been considerable recent interest in the isospin-2 multiplets in nuclei with mass numbers 20 and 24. The ground-state masses of the neutron-rich members of these multiplets are well known and many $T=2$ analog states have been reported and studied.[1,2] In $A=18$ and $A=22$ nuclei, the only information available on $T=2$ states has been a single measurement of the ground-state mass of ^{18}N and of ^{22}F. Excited states have not been reported in either ^{18}N or ^{22}F, and no $T=2$ analog states are known in nuclei with mass number 18 or 22. Information on isospin-2 states in mass-22 nuclei is particularly needed to complete the systematic study[3] of multiplets in the $d_{5/2}$ shell.

The previous information on ground-state masses of ^{18}N and ^{22}F consists of β-γ coincidence observations and measurements of β-endpoint energies. Chase *et al.*[4] have reported the production of the radionuclide ^{18}N through the ^{18}O$(n, p)^{18}$N reaction. By measuring the endpoint energy of β radiation emitted in coincidence with ^{18}O γ rays, the mass excess (^{12}C=0) of ^{18}N was determined to be 13.1±0.4 MeV. Likewise, Vaughn *et al.*[5] reported the production of ^{22}F through the ^{22}Ne$(n, p)^{22}$F reaction. The β-γ coincidence observations were not as clear in this case and the authors could not distinguish with complete certainty whether or not β transitions occurred to the ground state of ^{22}Ne. Their proposed decay scheme together with their β-endpoint energy measurement gives a mass excess of 4.5±0.6 MeV for ^{22}F.

In order to obtain more accurate mass values and to provide values which do not depend on interpretation of decay spectra, we have used the $(t, ^3$He$)$ reaction on ^{18}O and ^{22}Ne to observe the formation of ^{18}N and ^{22}F as residual nuclei. Ground-state masses were determined from the measured energy of the highest energy ^{3}He group. With the ^{22}Ne target, ^{3}He groups at lower energy provided first evidence for excited states in ^{22}F. In addition, inelastic scattering of protons, deuterons, and tritons from ^{22}Ne was studied to search for the $T=2$ analog states in ^{22}Ne.

APPARATUS AND PROCEDURE

The 22-MeV triton beam from the Los Alamos 3-stage tandem facility was used to bombard gas targets of ^{18}O and ^{22}Ne, and the energy spectra of ^{3}He particles were observed in an E-ΔE counter telescope. Figure 1 is a schematic drawing of the scattering geometry. The gas target consisted of a 3.8-cm-diam chamber with a flat entrance window and a cylindrical exit window. The entrance and exit windows are made of 2.5-μm Havar foil which was sufficient to contain gas pressures in the 200–300-Torr range. Three detectors were used in the counter telescope assembly as shown in Fig. 2. A ΔE proportional counter measured the rate of energy loss of the charged particles emerging from the gas target. The proportional counter gas consisted of a

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

[1] $A=20$: J. Cerny, R. H. Pehl, and G. T. Garvey, Phys. Letters **12**, 234 (1964); Phys. Rev. Letters **13**, 548 (1964); P. Loncke and J. Pradal, Phys. Letters **22**, 320 (1966); E. Adelberger and A. B. McDonald, *ibid.* **24B**, 270 (1967); H. M. Kuan, D. W. Heikkinen, K. A. Snover, F. Riess, and S. S. Hanna, *ibid* **25B**, 217 (1967).

[2] $A=24$: M. G. Silbert and N. Jarmie, Phys. Rev. **123**, 221 (1961); G. T. Garvey, J. Cerny, and R. H. Pehl, Phys. Rev. Letters **12**, 726 (1964); D. H. Wilkinson, Phys. Letters **11**, 243 (1964); F. G. Kingston, R. J. Griffiths, A. R. Johnston, W. R. Gibson, and E. A. McClatchie, *ibid.* **22**, 458 (1966); R. L. McGrath, S. W. Cosper, and J. Cerny, Phys. Rev. Letters **18**, 243 (1967); E. Adelberger and A. B. McDonald, Phys. Letters **24B**, 270 (1967); F. Riess, W. J. O'Connell, D. W. Heikkinen, H. M. Kuan, and S. S. Hanna, Phys. Rev. Letters **19**, 367 (1967).

[3] J. C. Hardy, H. Brunnader, and J. Cerny, Bull. Am. Phys. Soc. **13**, 561 (1968).

[4] L. F. Chase, Jr., H. A. Grensch, R. E. McDonald, and F. J. Vaughn, Phys. Rev. Letters **13**, 665 (1964).

[5] F. J. Vaughn, R. A. Chalmers, L. F. Chase, Jr., and S. R. Salisbury, Phys. Rev. Letters **15**, 555 (1965).

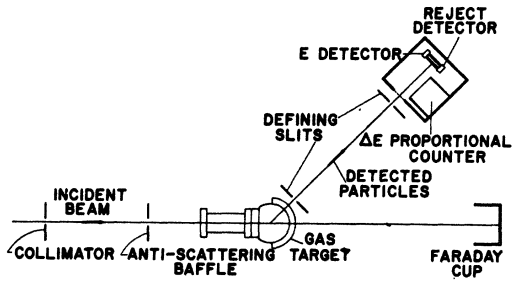

FIG. 1. Schematic diagram of the scattering geometry.

mixture of argon plus 10% CO_2 and had an equivalent silicon thickness of 15 to 22 μm at the two operating pressures used in the experiment. The 2.2-μm Havar foil entrance window of the ΔE counter is equivalent to 6 μm of Si. Thus, the ΔE detector for measurement of the lowest-energy ^{3}He spectra had an equivalent silicon thickness of 21 μm. The full aperture of the ΔE counter was 1.27 cm in diameter. Use of a proportional counter was necessary in order to provide a sufficiently thin detector which would permit low-energy ^{3}He ions to be identified. At the time of the experiment commercially available silicon ΔE detectors were not sufficiently thin and uniform over the required areas. In spite of improvements in silicon detectors it seems likely that proportional detectors will continue to be useful for ΔE measurements of particles with high rates of energy loss. When very small areal density is required, a proportional ΔE detector becomes an attractive choice to complement the use of silicon detectors in a range of greater thickness. The foremost advantages of a very thin ΔE proportional detector are: great uniformity of areal density, ability to change the areal density easily by changes of gas pressure, and freedom from radiation damage. This detector has been previously used in several other experiments[6] which required good ΔE measurements of low-energy hydrogen or helium ions.

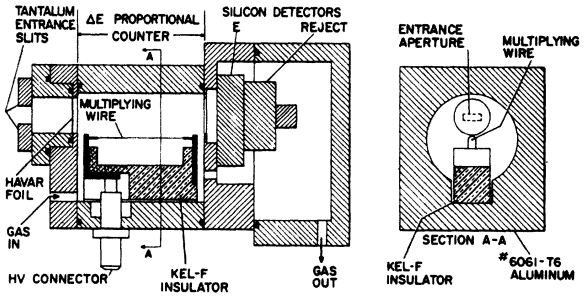

FIG. 2. Detector assembly. The multiplying wire of the ΔE proportional counter is parallel to the trajectory of detected particles.

[6] R. H. Stokes and P. G. Young, Phys. Rev. Letters **18**, 611 (1967); P. G. Young, R. H. Stokes, and G. G. Ohlsen, Phys. Rev. **173**, 949 (1968); G. G. Ohlsen, R. H. Stokes, and P. G. Young (to be published).

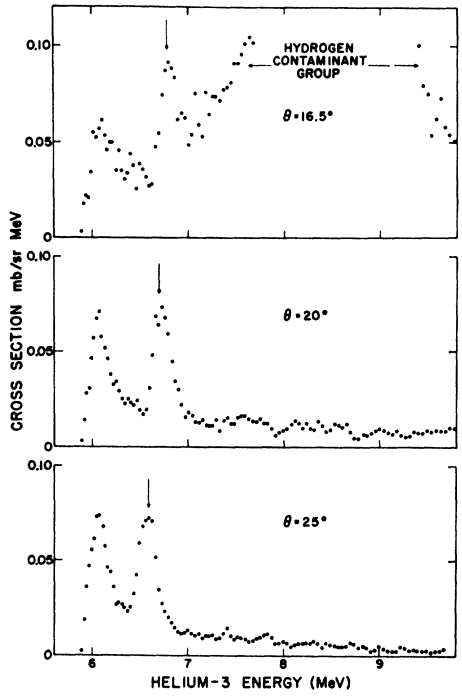

FIG. 3. ^{3}He energy spectra from the $^{18}O(t, {}^3He)^{18}N$ reaction for three laboratory angles. Arrows designate the ground-state group. The contaminant group from the $^1H(t, {}^3He)$ reaction has a kinematic limit of 18 deg and thus does not appear in the two lower spectra. Events below 6 MeV are rejected by the electronic logics as discussed in the text.

To measure the residual energy E, a 980-μm-thick silicon surface-barrier transmission detector was used. Following the E detector, a second silicon detector was used to provide a reject pulse for the more penetrating particles which passed through the previous detectors. A pair of tantalum collimators 0.16 cm wide, spaced 9.2 cm apart, was used to define the axis of the detected particles.

Data were collected with an SDS-930 on-line computer in an E by ΔE array of 128 by 64 channels. The analog-to-digital converters at the computer input were gated by a coincidence between E and ΔE. Curve-fitting

TABLE I. Excited states of ^{22}F.

Excited state	Excitation energy (MeV)
1	0.66±0.025
2	1.36±0.025
3	1.57±0.025
4	1.97±0.025
5	2.54±0.060
6	2.91±0.060

techniques were used to sort the E by ΔE two-dimensional arrays and to distinguish between the desired ^{3}He spectra and the more intense α-particle spectra. Finally, $E+\Delta E$ spectra were generated for each particle species. Cross sections of the $(t, {}^3\text{He})$ reactions are very low. The intensity of the ^{4}He spectra which must be rejected was typically a factor of 50–200 greater than the peak intensity of the desired ^{3}He spectra. A parallel electronics system containing an analog particle identifier and a 400-channel analyzer was used to monitor the ^{3}He energy spectra during data accumulation.

Data collection of the ^{18}N and ^{22}F spectra was interspersed with the collection of data used to establish the ^{3}He energy scale. Energy calibrations were obtained by using a triton energy of 22.0 and 17.0 MeV and observing ^{3}He groups of known Q value from the $^{14}\text{N}(t, {}^3\text{He})^{14}\text{C}$ reaction. During all data collection a stable pulser was connected through the complete electronic system and the pulser peak recorded in the computer. The pulser group showed no appreciable shift throughout the experiment. Background runs were

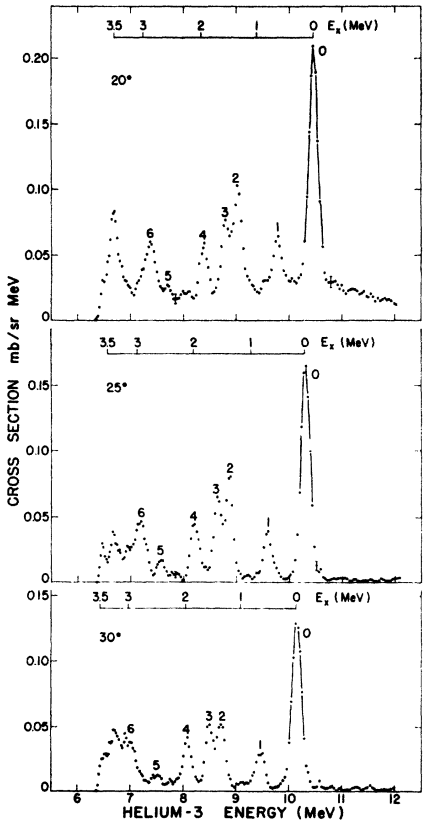

FIG. 4. ^{3}He energy spectra from the $^{22}\text{Ne}(t, {}^3\text{He})^{22}F$ reaction for three laboratory angles. The ground-state group is labeled 0, and the excited-state groups are labeled 1–6. Each spectrum has a scale of ^{22}F excitation energy at the top. The cutoff near 6 MeV is caused by the electronic logics.

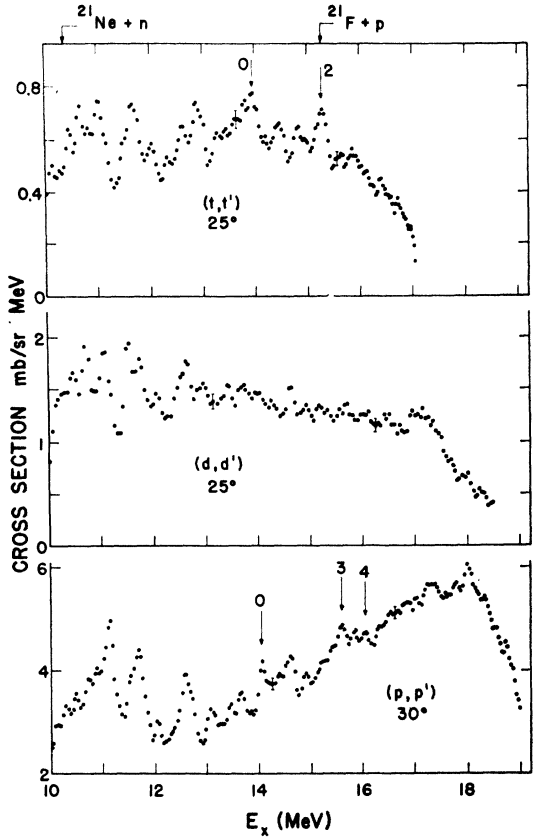

FIG. 5. Spectra from inelastic scattering with a ^{22}Ne target. The bottom scale is the excitation energy of ^{22}Ne as determined by measurements of the energy of the detected proton, deuteron, or triton. The vertical scales give the laboratory cross section. In all cases the bombarding energy was 22 MeV. The cutoff at the upper end of each spectrum is caused by the electronic logics.

taken with air, carbon dioxide, and nitrogen gases in the target. Groups from hydrogen contamination had an upper kinematic limit of 18° laboratory angle. The groups assigned to ^{18}N and ^{22}F were distinct from the particle groups which appeared in the background runs.

For the inelastic-scattering measurements, proton, deuteron, and triton beams of 22-MeV energy were used with the same apparatus and techniques described above. Energy calibrations were obtained using the $^4\text{He}(t, p)^6\text{He}$, $^3\text{He}(d, d)^3\text{He}$, and $^3\text{He}(t, t)^3\text{He}$ reactions.

DATA

The ground-state mass of ^{18}N was measured using the $^{18}\text{O}(t, {}^3\text{He})^{18}\text{N}$ reaction. The target gas (obtained from the Isotopes Division of the Oak Ridge National Laboratory) was enriched to 99.3% in ^{18}O. ^{3}He spectra were measured at several laboratory angles in the range 12–25 deg. Figure 3 shows sample spectra for laboratory angles of 16.5°, 20°, and 25°. Only the ground-state group appears above the ΔE-counter cutoff at 6-MeV ^{3}He energy. This cutoff occurs when the ^{3}He ions

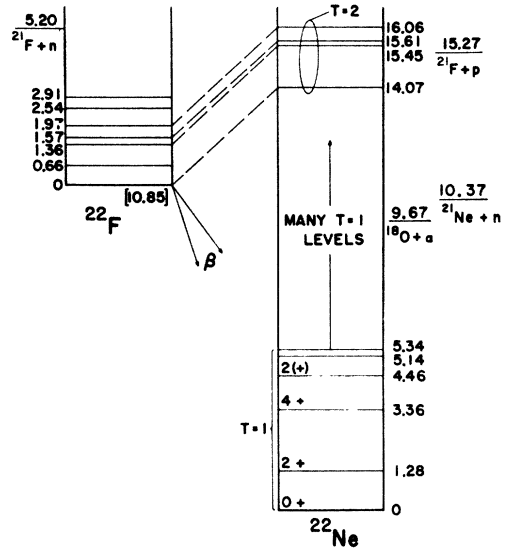

FIG. 6. Level diagram of ^{22}F and ^{22}Ne. The ^{22}F ground and excited states are shown along with the proposed $T=2$ analog states in ^{22}Ne. Data for the low excited states of ^{22}Ne were taken from Ref. 8.

have such a low energy that they do not pass through the ΔE detector and consequently no E pulse is generated to satisfy the coincidence requirement. The peak near 6-MeV ^{3}He energy arises from the combined effects of the ΔE cutoff and the background from neutrons and γ rays. Corrections for background have not been made to any of the spectra. The low level of the background is illustrated by a comparison with the 6.7 μb/sr value of center-of-mass cross section determined for the ^{18}N group at a laboratory angle of 20°. The measured Q value of the ground-state group is -14.038 ± 0.030 MeV, corresponding to a mass excess (^{12}C=0) of 13.274 ± 0.030 MeV. This value falls within the quoted errors of the previously measured value[4] of 13.1 ± 0.4 MeV. Our quoted error (standard deviation) results from nearly equal contributions from uncertainties in determining peak location, energy loss in the target gases, and the energy calibration. Values of cross section given in Fig. 3–5 have an estimated absolute error of $\pm15\%$. This error results principally from uncertainty in the value of the detector solid angle.

The ground-state mass of ^{22}F was measured using the ^{22}Ne(t, ^{3}He)^{22}F reaction. The target gas (obtained from the Mound Laboratory of the Monsanto Research Corporation) was enriched to 99.7% in ^{22}Ne. ^{3}He energy spectra were measured at laboratory angles of 20°, 25°, and 30°. Figure 4 shows these spectra. From the measured energy of the highest ^{3}He group the ground-state Q value was determined to be -10.834 ± 0.030 MeV, corresponding to a mass excess of 2.828 ± 0.030 MeV. This value differs markedly from the only previously proposed value[5] of 4.5 ± 0.6 MeV.

Evidence for excited states in ^{22}F was obtained from the other ^{3}He groups in the spectra. These excited-state groups are shown in Fig. 4 labeled 1–6. Table I lists the measured value of excitation energy and the assigned errors.

Energy spectra from the ^{22}Ne(p, p'), ^{22}Ne(d, d'), and ^{22}Ne(t, t') reactions were also measured to search for $T=2$ analog to ^{22}F states. The proton and triton reactions are allowed to form $T=2$ states, whereas the deuteron reaction is forbidden by isospin conservation. The deuteron spectra can be used as a guide in identifying peaks from $T=1$ states which will appear along with the $T=2$ states in the proton and triton spectra. Figure 5 shows these inelastic spectra as a function of ^{22}Ne excitation energy.

DISCUSSION AND CONCLUSIONS

The present measurements of the ground-state Q value of the ^{22}Ne(t, ^{3}He)^{22}F reaction result in a ^{22}F mass 1.67 MeV lower than the value previously reported.[5] The previous result was based on the measured β-ray endpoint energy (11.2 ± 0.6 MeV) for the decay of ^{22}F to ^{22}Ne and the conclusion that the 11.2 MeV decay goes to the 1.28 MeV first excited state of ^{22}Ne. Thus, the sum of these two energies (or 12.5 ± 0.6 MeV) was reported for the ^{22}F$-^{22}$Ne mass difference. On the basis of the coincidence observations of Ref. 5, however, one cannot exclude the existence of a direct β transition to the ^{22}Ne ground state. Further, our measurement of 10.853 ± 0.030 MeV for the ^{22}F$-^{22}$Ne mass difference is contained within the errors of their measurement of 11.2 ± 0.6 MeV for the β endpoint energy (see Fig. 6). This suggestion that the 11.2-MeV β branch proceeds to the ^{22}Ne ground state in turn revises the previous tentative assignment[5] of 3^+ to the ^{22}F ground state. The log ft value (6.4) of the 11.2-MeV group[5] lies within the empirical range for allowed transitions. An allowed β transition to the 0^+ ground state of ^{22}Ne would suggest an assignment of 1^+ for the ground state of ^{22}F. Since ^{22}F is probably a strongly deformed nucleus, a spin of 1^+ for its ground state could be explained as resulting from parallel coupling of the Nilsson[7] orbitals $\frac{1}{2}^+[220]_p$ and $\frac{1}{2}^+[211]_n$, which are reasonable state assignments for the odd proton and odd neutron, respectively. If the 1^+ assignment for ^{22}F is correct, it follows that the suggested[5] β branch to the 3.36-MeV (4^+) level of ^{22}Ne does not exist. It is therefore possible that the $\approx$2.08-MeV γ rays reported to accompany the ^{22}F decay[5] arise from the β population of a higher-lying state of low spin, with subsequent de-excitation through the 3.36-MeV level. For example, population of the 5.52-MeV level of ^{22}Ne, which is known to de-excite[8] mainly through a 2.16-2.08-1.28-MeV cascade, would give rise to a

[7] S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. **29**, No. 16 (1955).
[8] W. Kutschera, D. Pelte, and G. Schrieder, Nucl. Phys. **A111**, 529 (1968).

2.16-2.08-MeV doublet that might be responsible for the peak at about 2.1 MeV observed by Vaughn *et al.*[5] This suggestion, however, requires the spin of the 5.52-MeV level to be 2^+, in disagreement with the tentative conclusion of Ref. 8 that the spin is (3, 4, 5, 6). It is conceded that there may be other ways of reconciling the present data with the results of Ref. 5. It is also clear that the various questions raised above cannot be answered in detail until more complete information exists on the ^{22}F decay.

Except for the ^{18}N ground state, no isospin-2 states are known in nuclei with mass number 18. The more accurate mass value from the present experiment will furnish a basis for productive future searches for mass-18 analogs. Likewise, in nuclei with mass number 22, the only $T=2$ states known are the ground state and the excited states reported here. With the accurate location of the low-lying states in ^{22}F, it is now possible to proceed with a search for their analogs.

In order to estimate the Coulomb-energy differences in A=22 nuclei, we use the expression derived from the Coulomb energy of a uniformly charged sphere of radius $r=r_0A^{1/3}$. The Coulomb-energy difference between a member of an isospin multiplet of mass number A and charge Z and the adjacent member of the multiplet of charge $Z+1$ is $\Delta E_c=KZ/A^{1/3}$ MeV, where $K=1.73/r_0$ and r_0 is in Fermis. Table II lists information from various known isospin multiplets in the vicinity of $A=22$ and the values of K derived from each. The range of values is small and centers about $K=1.22$ ($r_0=1.42$ F). This value can then be used to calculate the energy difference between the ^{22}F ground state and its analog in ^{22}Ne as $\Delta E=\Delta E_c-0.782$ MeV where 0.782 MeV is the ^1H-n mass difference. The result is that the lowest $T=2$ state in ^{22}Ne should occur near an excitation energy of 13.99 MeV above the ground state.

TABLE II. Coulomb-energy data. For mass numbers 20–24 Coulomb energy shifts have been calculated for the highest isospin multiplet in which two or more members are known. Single or repeated application of the formulas $\Delta E=\Delta E_c-0.782$, and $\Delta E_c=KZ/A^{1/3}$ were used to derive values of K. See the text for notation. Except as noted, the values of mass used to determine K were taken from Thiele and Wapstra, and Maples *et al.*[a]

A	T	Nuclei used	Reference	K
20	2	^{20}Ne–^{20}O	b	1.19
21	$\frac{3}{2}$	^{21}Mg–^{21}F		1.20
22	1	^{22}Mg–^{22}Ne	c	1.23
23	$\frac{1}{2}$	^{23}Mg–^{23}Na		1.25
24	2	^{24}Mg–^{24}Ne	b	1.23
			Average $K=1.22$	

[a] See Ref. 11.
[b] E. Adelberger and A. B. McDonald, Phys. Letters **24B**, 270 (1967).
[c] A. B. McDonald and E. G. Adelberger, Bull. Am. Phys. Soc. **12**, 1145 (1967).

TABLE III. Tentative locations of $T=2$ states in ^{22}Ne. Excitation-energy values E_x, are listed for the $T=2$ states of ^{22}Ne identified through the ^{22}Ne(p,p'), ^{22}Ne(t,t'), and ^{22}Ne(d,d') reactions. For states 0, 3, and 4, the values of excitation energy were derived from the ^{22}Ne(p,p') data for which the energy calibrations [from the ^{4}He(t,p)^{6}He reaction] were done most accurately. The energy of state 2 was determined by using the 0–2 energy difference from the ^{22}Ne(t,t') spectrum. State 0 is within 0.08 MeV of the estimate (see text) of the position of the analog to the ^{22}F ground state. The column labeled ΔE is the energy difference between the three higher states and state 0. The numbers in parentheses are excitation energies of the corresponding ^{22}F excited state.

State number	E_x (MeV)	ΔE (MeV)
0	14.07±0.040	
2	15.40±0.050	1.33 (1.36)
3	15.61±0.060	1.54 (1.57)
4	16.06±0.060	1.99 (1.97)

Figure 6 summarizes the energetics in ^{22}Ne and shows the energy of the lowest particle breakup threshold through which a $T=2$ state is allowed to decay. The predicted energy of the lowest analog (13.99 MeV) is 1.28 MeV below the lowest $T=2$ breakup threshold (^{21}F+p). If the analog state has high isospin purity, it should not be broadened by the $T=1$ decay channels with thresholds which lie below, and it should be possible to observe it as a narrow state lying on a dense background of $T=1$ states. Possibly this analog state had not been searched for previously since the former mass value of ^{22}F would have put it above the ^{21}F+p breakup threshold, and the state would be expected to have a large width.

In Fig. 5 both the ^{22}Ne(p, p') and the ^{22}Ne(t, t') spectra have a peak (designated by an arrow marked 0) occurring near 14-MeV excitation energy. A peak does not appear at a similar excitation energy in the ^{22}Ne(d, d') spectrum, a behavior which is consistent with isospin conservation for a $T=2$ state in the final nucleus. The value determined for the excitation energy of this state is 14.07±0.04 MeV. This measured energy differs by only 0.08 MeV from the value of 13.99 MeV which was predicted for the lowest $T=2$ state in ^{22}Ne. The predicted value was derived from values of K (Table II) which have a full range of ±0.03. To estimate reasonable outer limits of the Coulomb-energy shift, a range of K values with *twice* this spread or 1.22±0.06 will be assumed. These limits correspond to a range of excitation energy in ^{22}Ne of 13.80 to 14.18 MeV. In the (p, p') spectrum of Fig. 5 the only peak in this range is the one at 14.07 MeV. Further, this peak has an observed width only slightly greater than that of the measuring system (0.15 MeV), and thus corresponds to a state whose width is much less than this value. The width of peak 0 can be compared with that of known

$T=1$ states which appear in the ^{22}Ne(p, p') spectrum. For example, we observe a peak which results from a known state[9] at 12.63 MeV in ^{22}Ne. This state, which we expect to have $T=1$, lies 3 MeV above the lowest $T=1$ breakup threshold (^{18}O$+\alpha$) and 2.3 MeV above ^{21}Ne$+n$. The observed width of this peak at 12.63 MeV is 0.3 MeV or twice the width of the experimental system alone, and thus it exhibits considerable broadening as expected for $T=1$ states which are heavy particle unstable to $T=1$ decay modes. As mentioned above, the ^{22}Ne(p, p') peak marked 0 is observed to have a width appreciably less than 0.15 MeV. If we assume that state 0 has $T=2$, then even though it lies 4.4 MeV above ^{18}O$+\alpha$ (and 3.7 MeV above ^{21}Ne$+n$) it should not be greatly broadened since it lies 1.2 MeV below the lowest $T=2$ decay threshold (^{21}F$+p$). Finally, the peaks marked 2, 3, and 4 are spaced in energy with respect to peak 0 by amounts which are close to the measured spacing for the second, third, and fourth excited states in ^{22}F. This is summarized in Table III where the energies and assigned errors are listed for peaks 0, 2, 3, and 4. In summary, we believe that the data on isospin conservation, Coulomb-energy difference, the observed energy widths, and the observed energy spacings of peaks 0, 2, 3, and 4 suggest that they are analogs to the ground, second, third, and fourth excited states in ^{22}F. In the future, it would be valuable to confirm these tentative assignments by direct reaction studies which measure the complete angular distribution of the inelastic spectra.

From the mass of ^{22}F and the Coulomb-energy relations used above, it is possible to predict a mass for ^{22}Al, the unreported proton-rich mirror of ^{22}F. The value $K=1.22$ gives a mass for ^{22}Al which is 0.08 MeV above the ^{21}Mg$+p$ breakup threshold. This estimate shows that ^{22}Al is very near the proton-stability limit, whereas the previously accepted ^{22}F mass[5] indicated that ^{22}Al would certainly be unstable to proton decay.

Knowledge of the ground-state masses of ^{18}N and ^{22}F also leads to conclusions regarding the neutron stability of the unreported nuclei ^{19}N, ^{21}O, and ^{23}F. On the basis of the systematics of nucleon pairing energies,[10] limits can be set on the ground-state mass of these three nuclei. For ^{19}N, the definition of neutron-pairing energy of the last two neutrons results in the expression $\mathrm{NPE}(^{19}\mathrm{N})=2M(^{18}\mathrm{N})-M(^{17}\mathrm{N})-M(^{19}\mathrm{N})$, where M is the mass or mass excess[11] of the nucleus indicated. The neutron-pairing energy for a given number of neutron pairs has a consistent oscillatory behavior as protons are added.[10] This behavior enables one to state that the value of NPE(^{19}N) is less than the known value of NPE(^{20}O), which is 3.67 MeV. Also, the pairing energy is not less than zero. These considerations determine that $B_n(^{19}\mathrm{N})$, the neutron binding energy, lies between 2.7 and 6.3 MeV, and thus ^{19}N is predicted to be neutron stable. Calculations based on the independent-particle model by Garvey and Kelson[12] predict a value of $B_n=5.0$ MeV for ^{19}N. Because of the factor of 2 in the NPE relation, the predicted mass of ^{19}N is particularly sensitive to the mass value of ^{18}N. This is also true for the mass value of ^{22}F in the predictions which will be made concerning ^{21}O and ^{23}F.

Limits can be set on the mass of ^{21}O by use of the analogous relation for the proton-pairing energy of ^{23}Ne, that is, $\mathrm{PPE}(^{23}\mathrm{Ne})=2M(^{22}\mathrm{F})-M(^{21}\mathrm{O})-M(^{23}\mathrm{Ne})$. If the value of PPE(^{23}Ne) is taken to lie between 0 and 4.13 MeV (the value of PPE for ^{22}Ne), a range of 1.1–5.2 MeV results for the neutron binding energy of ^{21}O. Thus, ^{21}O is predicted to be stable to neutron emission, whereas if the former mass for ^{22}F is used, the limits set do not preclude neutron instability.[13] This result is also consistent with the predictions of Garvey and Kelson[12] who obtain $B_n=1.2$ MeV for ^{21}O.

Finally, from the relation $\mathrm{NPE}(^{23}\mathrm{F})=2M(^{22}\mathrm{F})-M(^{21}\mathrm{F})-M(^{23}\mathrm{F})$, limits can be set on the neutron binding of ^{23}F. In this case we take NPE(^{23}F) to lie between 0 and 3.68 MeV (the value of NPE for ^{24}Ne). This gives a range of $B_n=5.2$–8.9 MeV, indicating that ^{23}F is also neutron stable. These predictions are generally consistent with previous evidence,[14] which indicates that many more neutron-rich light nuclei will be discovered before the limits of neutron stability are reached.

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