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Energy Levels of F^{20} up to 6.043-MeV Excitation*

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The reactions $O^{18}(He^3,p)F^{20}$ and $F^{19}(d,p)F^{20}$ have been used to study levels in F^{20} up to an excitation energy of 6.043 MeV. The energies of the reaction protons were measured with a broad-range magnetic spectrograph. Excitation energies were obtained for 45 levels in F^{20}. The ground-state Q values for the above reactions were also measured and found to be 6.8752 ± 0.0015 MeV for the $O^{18}(He^3,p)F^{20}$ reaction and 4.3777 ± 0.0009 MeV for the $F^{19}(d,p)F^{20}$ reaction.

INTRODUCTION

The low-lying excited levels of F^{20} have been studied mainly with the $F^{19}(d,p)F^{20}$ reaction. Watson and Buechner[1] measured the excitation energies for 19 levels up to 4.31 MeV with typical uncertainties of ±8 keV. Later, Rickards[2] used the same reaction to measure levels up to 3.68-MeV excitation with stated uncertainties of ±4 keV. Using the $O^{18}(He^3,p)F^{20}$ reaction it was shown[3] that there were actually two levels in the vicinity of 1.85 MeV with excitation energies of 1.824 and 1.843 MeV. No precision charged-particle energy measurements have been made above 4.31-MeV excitation, although six levels have been observed by El-Bedewi[4] in the region from 5 to 6 MeV with stated uncertainties of ±20 keV.

The most accurate determination of excitation energies in F^{20} has been the work of Spilling *et al.*,[5] who used a lithium-drifted germanium detector to measure γ-ray energies from the $F^{19}(n,\gamma)F^{20}$ reaction. The stated uncertainties are better than ±0.6 keV for the excitation energies obtained. The same reaction has also been studied by Hardell and Hasselgren[6] using a Ge(Li) spectrometer. The uncertainties in the measured excitation energies were ±1 to ±2 keV. Most recently, excitation energies have been determined by Holtebekk, Tryti, and Vamraak[7] from γ-ray measurements in the $F^{19}(d,p\gamma)F^{20}$ reaction.

The purpose of the present experiment is twofold. The first is to obtain more precise values for the excitation energies of the known states in F^{20} using precision charged-particle energy measurements. The excitation energies thus obtained may be compared with the results of the precision γ-ray energy measurements. The charged-particle energy measurement also provides accurate excitation energies for the low-lying states not obtained from the γ-ray measurements. The second purpose of the present experiment is to investigate the region of excitation in F^{20} between 4.31 and 6.04 MeV, where very few accurate excitation energies are known. A precise knowledge of the higher-lying excited states in F^{20} may also prove useful in resolving some ambiguities which may arise in the interpretation of high-resolution γ-ray spectra.

In the present investigation a broad range magnetic spectrograph was used to obtain excitation energies in F^{20} up to 4.08 MeV using the $F^{19}(d,p)F^{20}$ and $O^{18}(He^3,p)F^{20}$ reactions. The excitation energy region from 4.08 to 6.04 MeV was studied using the $F^{19}(d,p)F^{20}$ reaction. The ground-state Q values for these two reactions have also been measured and the mass excess of F^{20} has been calculated from the results.

EXPERIMENTAL PROCEDURE

The broad-range magnetic spectrograph used in these measurements has been previously described in detail.[8] The reaction products were momentum-analyzed and detected in nuclear emulsions. The spectrograph calibration is based on a Po^{210} $\alpha B\rho$ of 331.766 kG cm. The Notre Dame 4-MeV accelerator was used to provide the deuteron and He^3 beams.

The O^{18} targets were obtained by anodizing one side of a 0.005-in. tantalum foil in a solution of $Na_2B_4O^{18}{}_7$ in D_2O^{18}. The resulting oxide coatings were 10- to 20-keV thick for the 4-MeV He^3 beam. For the $F^{19}(d,p)F^{20}$ experiment the targets used were either CaF_2 or Li^7F evaporated onto a 10-μg/cm^2 carbon backing. Target thickness ranged from 5 to 20 keV.

RESULTS

$O^{18}(He^3,p)F^{20}$ Reaction

This reaction was studied at bombarding energies of 3.8 and 4.0 MeV and reaction angles of 70, 80, 90, 110, and 130°. The incident beam energy was determined by measuring the energy of the He^3 particles elastically scattered from the tantalum backing, with the target reversed so that the

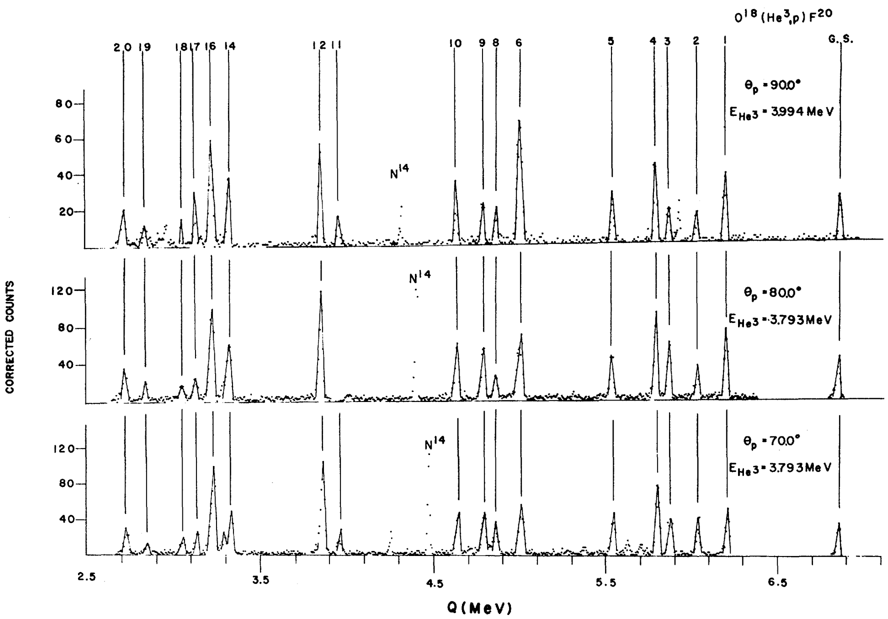

FIG. 1. Spectra of protons from the $O^{18}(He^3,p)F^{20}$ reaction at laboratory angles of 70, 80, and 90°, and bombarding energies of 3.793 and 3.994 MeV. The ordinate is the number of proton tracks in a $\frac{1}{2}\times 10$-mm strip of emulsion after converting from plate distance to Q value and applying corrections for change in solid angle along the plate and conversion from lab to c.m. The contaminant group shown arises from the $C^{12}(He^3,p)N^{14}$ reaction.

beam struck the uncoated side. For some of the measurements the beam energy was determined by substituting a thin gold target and measuring the elastically scattered He^3 particles. Aluminum absorber foils were placed on that portion of the emulsion used for recording proton tracks in order to remove the large background of $(He^3)^+$ ions elastically scattered from the thick tantalum backing.

Proton spectra for three observation angles are shown in Fig. 1. The numbered peaks correspond to levels in F^{20}. The effective target thickness for the runs shown was about 30 keV so the 1.824- and 1.843-MeV levels are not resolved. These levels have been resolved in other runs as has been previously reported.[3] The measured excitation energies for the levels in F^{20} observed in this reaction are given in Table I. The standard deviations of the mean σ_m and the internal errors e_{int} are given. These were calculated from the expressions

$$\sigma_m = \left[\frac{\sum w_l \delta_l^2}{(n-1)\sum w_l}\right]^{1/2},$$

$$e_{int} = [\sum 1/(\Delta E_l)^2]^{-1/2},$$

where the w_l are weighting factors, the δ_l are the deviations of each measurement from the mean, n is the number of measurements, and the ΔE_l are the uncertainties assumed to exist in any one given measurement. For the excitation energy measurements all the data were given equal weighting factors.

An error of 0.1% of the excitation energy has been assumed for each run.[3] An additional error ranging from 1 to 5 keV has been assumed for each run because of poor statistics, which give rise to an uncertainty in determining the one-third height of a peak.

The error stated in the last column of Table I is obtained by combining the statistical uncertainty, which is taken as the larger of the standard deviation of the mean and the internal error, with the

TABLE I. Energy levels in F^{20} observed in the $O^{18}(He^3,p)F^{20}$ reaction at a bombarding energy of 3.8 and 4.0 MeV. See text for explanation of the errors. All excitation energies are obtained by measuring the separation energy from the 3681.0-keV state. The excitation energy used for this level is 3681.0 ±2.5 keV as measured in the $O^{18}(He^3,p)F^{20}$ reaction.

Level	Excitation energy (keV)	σ_m (keV)	e_{int} (keV)	Error (keV)
1	657.2	0.5	1.3	1.3
2	823.5	1.0	1.4	1.5
3	982.9	1.4	1.3	1.3
4	1058.1	1.1	1.3	1.4
5	1309.1	0.8	1.4	1.4
6	1824.4	0.6	1.5	1.6
7	1843.0	0.9	1.6	1.7
8	1971.9	1.3	1.5	1.6
9	2044.0	1.0	1.5	1.6
10	2195.5	1.3	1.9	2.0
11	2868.2	2.2	2.2	2.3
12	2967.1	1.1	1.8	2.0
14	3487.8	1.1	1.9	2.2
16	3586.3	1.1	2.0	2.2
17	3681.0	0.9	2.2	2.5
18	3761.0	1.6	2.9	3.1
19	3966.9	0.9	2.6	2.8
20	4083.7	1.2	2.6	2.9

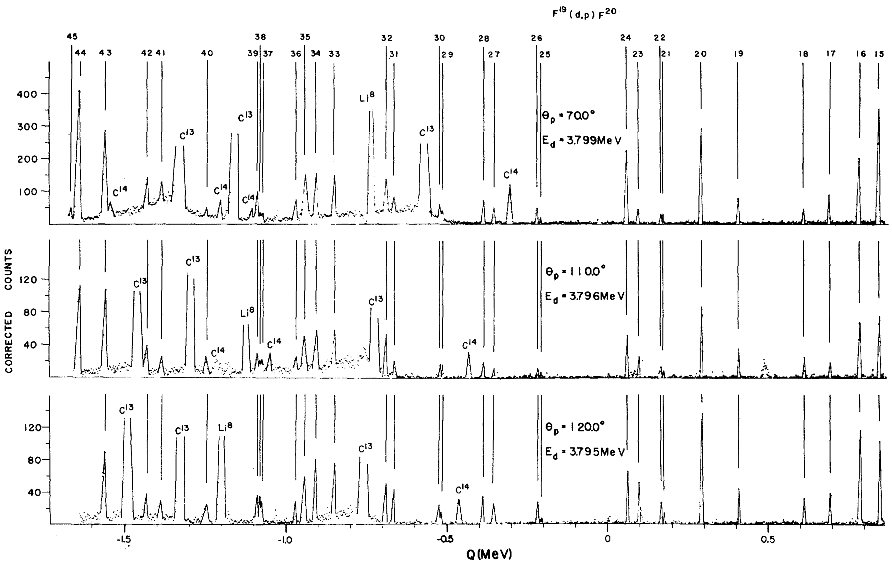

FIG. 2. Spectra of protons from the $F^{19}(d,p)F^{20}$ reaction at laboratory angles of 70, 110, and 120°, and bombarding energies of 3.799, 3.796, and 3.795 MeV. Prominent contaminant groups are labelled by the symbol of the recoil nucleus.

spectrograph calibration uncertainty. An uncertainty of 0.03% of the excitation energy has been adopted for the error in the shape of the calibration curve.

$F^{19}(d,p)F^{20}$ Reaction

The low-lying states of F^{20} were observed by bombarding CaF_2 and Li^7F targets with a 1.8-MeV deuteron beam and observing the reaction products at 120 and 130°. The input deuteron energy was obtained from the deuterons elastically scattered from F^{19} and observed at the same time as the protons. The results of five such measurements are shown in Table II, with the errors obtained as discussed in the previous section. The 1.972- and 2.044-MeV levels were obscured by an intense contaminant group from the $C^{12}(d,p)C^{13}$ reaction. The 1.824-MeV level was too weakly excited to obtain a reliable energy measurement.

The region of excitation above 3.4 MeV in F^{20} was investigated by bombarding Li^7F targets with

TABLE II. Energy levels in $F^{2(}$ observed in the $F^{19}(d,p)F^{20}$ reaction at a bombarding energy of 1.8 MeV. See text for explanation of the errors.

Level	Excitation energy (keV)	σ_m (keV)	e_{int} (keV)	Error (keV)
1	654.9	0.2	1.0	1.0
2	821.6	0.5	1.0	1.0
3	983.3	0.4	1.0	1.0
4	1056.3	0.2	1.0	1.0
5	1310.8	0.3	1.0	1.1
7	1843.4	0.6	1.1	1.2
10	2195.1	0.4	1.3	1.5
11	2863.7	0.5	1.4	1.6
12	2966.6	0.3	1.5	1.7
13	3171.8	0.3	1.9	2.2

3.8-MeV deuterons and observing the reaction products at 70, 90, 100, 110, and 120°. Proton spectra for three of these runs are shown in Fig. 2. Levels are assigned as belonging to F^{20} if they appear at the proper energy on at least three of the runs, although most of the levels appear on all five runs. Prominent contaminants are identified by the symbol of the recoil nucleus. Since the ground-state group was not observed, the excitation energies were obtained by measuring the separation energy from the 3.681-MeV state in F^{20} whose excitation energy had been measured in the $O^{18}(He^3,p)F^{20}$ reaction as previously described. The excitation energies thus obtained are given in Table III. An error of 0.1% of the separation energy was assumed in calculating the internal error. The standard deviation and the internal error provide a measure of the uncertainty in the separation energy while the final error includes the ±2.5-keV uncertainty for the excitation energy of the 3.681-MeV state. An additional uncertainty of 0.03% of the separation energy has been included for the error in the shape of the calibration curve.

The closely spaced group of levels at 5.450, 5.455, and 5.463 MeV are not completely resolved in any of the measurements. There is, however, some indication for the presence of three closely spaced levels at all five angles of observation.

Mass of F^{20}

The ground-state Q value for the $O^{18}(He^3,p)F^{20}$ reaction obtained in the present experiment is 6.8752 ± 0.0015 MeV. The stated error is the internal error for the six measurements as previously defined. The uncertainty for each individual measurement used in calculating the internal error

TABLE III. Energy levels in F^{20} observed in the $F^{19}(d,p)F^{20}$ reaction at a bombarding energy of 3.8 MeV. See text for explanation of the errors. All excitation energies obtained by measuring the separation energy from the 3681.0-keV state. The excitation energy used for this level is 3681.0 ±2.5 keV as measured in the $O^{18}(He^3, p)F^{20}$ reaction.

Level	Excitation energy (keV)	σ_m (keV)	e_{int} (keV)	Error (keV)
15	3525.5	0.8	0.5	2.6
16	3586.4	1.1	0.5	2.7
17	3681.0			2.5
18	3760.8	1.0	0.5	2.7
19	3964.5	0.5	0.5	2.5
20	4080.9	0.5	0.5	2.5
21	4198.9	1.1	0.5	2.7
22	4207.7	0.7	0.5	2.6
23	4276.3	1.2	0.6	2.8
24	4311.5	0.6	0.6	2.6
25	4583.8	1.6	0.7	3.0
26	4592.2	1.4	0.6	2.9
27	4730.2	1.5	0.6	2.9
28	4763.8	1.0	0.6	2.7
29	4891.6	1.2	0.7	2.8
30	4898.2	1.2	0.7	2.8
31	5040.2	1.8	0.8	3.1
32	5065.5	1.9	0.8	3.1
33	5224.0	1.8	0.8	3.1
34	5281.0	2.0	0.8	3.3
35	5317.1	1.0	1.0	2.7
36	5344.5	2.1	1.0	3.3
37	5450.3	2.7	1.0	3.8
38	5455.4	1.9	1.0	3.2
39	5463.4	2.1	1.0	3.3
40	5620.3	2.0	1.0	3.3
41	5762.8	2.2	1.2	3.4
42	5809.1	0.1	1.4	2.9
43	5933.9	2.1	1.4	3.3
44	6015.0	2.7	1.3	3.8
45	6043.3	2.6	1.3	3.7

was assumed to be 0.04% of the Q value for spectrograph calibration uncertainty.[8] An additional uncertainty of 2 to 3 keV has been included because of poor statistics in the ground-state proton group which gives an uncertainty in the measurement of the position of the group. An uncertainty of 0.1 mm in the position on the plate for the elastically scattered He^3 particles was assumed. The uncertainty in the reaction angle was taken to be ±4 min. The standard deviation of the mean for the six runs was 0.0013 MeV.

Using the masses tabulated by Mattauch, Thiele, and Wapstra[9] for O^{18}, He^3, and p, and the above measured Q value, a mass excess for F^{20} of -0.0153 ± 0.0016 MeV was obtained.

The ground-state Q value for the $F^{19}(d,p)F^{20}$ reaction obtained in the present experiment was 4.3777 ± 0.0009 MeV. The stated error is once again the internal error. The standard deviation of the mean for the five measurements was 0.0008 MeV. Using this Q value, the mass excess of F^{20} was calculated to be -0.0168 ± 0.0011 MeV.

For comparison purposes a calculation of the mass excess of F^{20} was also made from the $F^{19}(n,\gamma)F^{20}$ reaction, using the value $Q_0 = 6.6011 \pm 0.0003$ MeV obtained by Spilling *et al.*[5] The resulting mass excess of -0.0157 ± 0.0009 MeV is in excellent agreement with the present results from the charged-particle measurements. Using the value of Hardell and Hasselgren[6] of $Q_0 = 6.6020 \pm 0.0006$ for the $F^{19}(n,\gamma)F^{20}$ reaction, one obtains a mass excess of F^{20} of -0.0166 ± 0.0010 MeV.

These results may be compared with the mass excess of F^{20} given in the 1964 mass tables[9] as -0.0119 ± 0.0047 MeV.

COMPARISON OF RESULTS

The results of the present measurements are shown in Table IV and in Fig. 3 along with previous results from other experiments. The final values for excitation energies for the present work were obtained by taking the unweighted mean of the results obtained from the $O^{18}(He^3, p)F^{20}$ and $F^{19}(d, p)F^{20}$ experiments. Excellent agreement is obtained between the two experiments. The largest discrepancy is 4.5 keV for the 2.865-MeV state, while the average discrepancy is 1.5 keV.

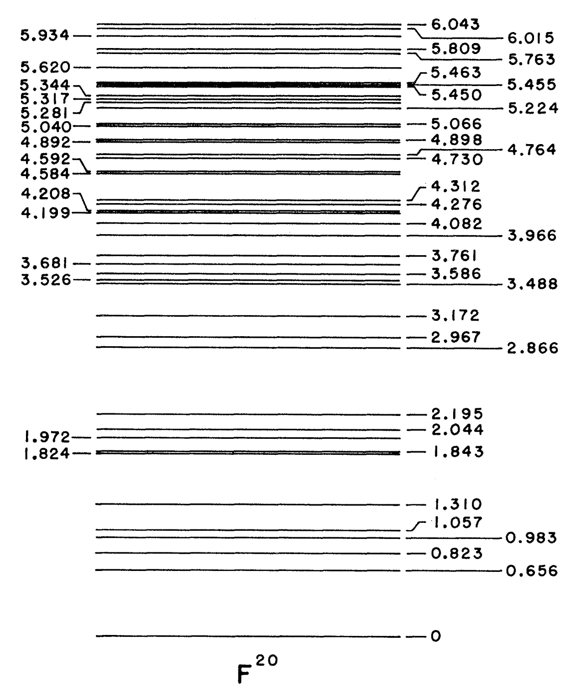

FIG. 3. Energy-level diagram of F^{20} showing those levels observed in the present work. Excitation energies given are the average of the results from the $O^{18}(He^3,p)F^{20}$ and $F^{19}(d,p)F^{20}$ experiments.

TABLE IV. Summary of excitation energies found for F^{20} and comparison with previous results.

	Charged-particle measurements					γ-ray measurements		
Level	Present work (keV)	Watson[a] (keV)	Rickards[b] (keV)	El-Bedewi[c] (MeV)	Khromchenko[d] (MeV)	Spilling[e] (keV)	Hardell[f] (keV)	Holtebekk[g] (keV)
1	656.0 ±1.1	652 ±8	660 ±4		0.66	656.3 ±0.3	656 ±1	655.9 ±0.2
2	822.6 ±0.9	828 ±8	828 ±4		0.81	822.9 ±0.3		823.0 ±0.3
3	983.1 ±0.8	988 ±8	989 ±4			983.9 ±0.3	984 ±1	983.9 ±0.3
4	1057.2 ±0.9	1059 ±8	1064 ±4		1.08	1057.2 ±0.3	1057 ±1	1057.0 ±0.2
5	1310.0 ±0.8	1309 ±8	1312 ±4		1.34	1309.1 ±0.3	1309 ±1	1309.3 ±0.2
6	1824.4 ±1.6							
7	1843.2 ±1.0		1851 ±4			1843.4 ±0.3	1843 ±1	1843.5 ±0.7
8	1971.9 ±1.6	1970 ±8	1975 ±4			1970.6 ±0.3		
9	2044.0 ±1.6	2048 ±8	2050 ±4			2044.2 ±0.4	2044 ±1	2043.7 ±0.5
10	2195.3 ±1.2	2195 ±8	2200 ±4		2.15	2194.5 ±0.6	2194 ±1	2194.5 ±0.6
					(2.54)			
11	2866.0 ±2.2	2870 ±8	2877 ±4					
12	2966.9 ±1.3	2966 ±8	2979 ±4			2965.8 ±0.5	2966 ±1	2966.8 ±0.6
13	3171.8 ±2.2		3184 ±4		3.11			3175.6 ±1.3
14	3487.8 ±2.2	3491 ±8	3499 ±4			3488.3 ±0.3	3488 ±1	3488.5 ±0.3
15	3525.5 ±2.6	3528 ±8	3538 ±4		3.58	3526.0 ±0.5		3525.9 ±0.5
16	3586.4 ±1.7	3586 ±8	3598 ±4			3587.3 ±0.3	3588 ±1	3586.5 ±0.6
17	3681.0 ±2.5	3681 ±8				3681.0 ±0.4	3681 ±1	
18	3760.9 ±2.0				3.77			
19	3965.7 ±1.9	3961 ±9					3967 ±1	
20	4082.3 ±1.9	4079 ±9			4.09	4082.2 ±0.5	4085 ±1	
21	4198.9 ±2.7							
22	4207.7 ±2.6							
23	4276.3 ±2.8	4275 ±9				4276.7 ±0.5	4275 ±1	
24	4311.5 ±2.6	4310 ±9			4.37			
25	4583.8 ±3.0				4.55			
26	4592.2 ±2.9							
27	4730.2 ±2.9				(4.73)			
28	4763.8 ±2.7							
29	4891.6 ±2.8				4.86			
30	4898.2 ±2.8							
31	5040.2 ±3.1			5.04				
32	5065.5 ±3.1	5062 ±11						
33	5224.0 ±3.1			5.19	5.16			
34	5281.0 ±3.3			5.27				
35	5317.1 ±2.7							
36	5344.5 ±3.3							
					5.41	5413.1 ±0.6		
37	5450.3 ±3.8							
38	5455.4 ±3.2							
39	5463.4 ±3.3							
					5.54	5554.7 ±0.6		
40	5620.3 ±3.3							
				5.72			5713 ±2	
41	5762.8 ±3.4							
42	5809.1 ±2.9							
				5.87				
43	5933.9 ±3.3			5.95		5936.0 ±0.3	5937 ±1	
44	6015.0 ±3.8					6017.3 ±0.3	6018 ±1	
45	6043.3 ±3.7				6.07	6044.6 ±0.4		

[a]See Ref. 1.
[b]See Ref. 2.
[c]See Ref. 4.
[d]See Ref. 10.
[e]See Ref. 5.
[f]See Ref. 6.
[g]See Ref. 7.

The present results for the low-lying states are also in good agreement with those of Watson and Buechner[1] with an average discrepancy of 2.6 keV, although the uncertainties in the present experiment are much smaller than those given by Watson and Buechner. Comparison with the results of Rickards indicates a systematic discrepancy which increases with excitation energy to about 12 keV for the states above 2.865 MeV.

The agreement with the excitation energies obtained from the γ-ray energy measurements of Spilling are excellent. The maximum discrepancy is 2.3 keV, while the average discrepancy is only 0.7 keV.

For the region of excitation above 4.08 MeV, very few precision excitation energies are available for comparison. The level structure of F^{20} in the region from 4 to 6 MeV is considerably more complicated than has been previously reported. As a result it is sometimes difficult to determine which of the levels observed in the present experiment correspond to those seen by El-Bedewi. The level reported at 5.04 MeV may correspond to either the 5.040- or the 5.065-MeV level or to an unresolved combination of the two. The nearest level seen in the present experiment to the 5.72-MeV state reported by El-Bedewi is a level at 5.763 MeV, although Hardell observes γ rays which might be attributed to the decay of a level at 5.713 MeV. No evidence is seen for the level reported by El-Bedewi at 5.87 MeV, although this region is partially obscured by the strong group arising from the $C^{12}(d,p)C^{13}$ reaction at several observation angles. No good evidence is seen for the levels reported by Khromchenko[10] at 5.41 and 5.54 MeV and given by Spilling as having excitation energies of 5.413 and 5.555 MeV, respectively. There is, however, a very weak peak which is observed at only two observation angles and could correspond to a level in F^{20} at about 5.407 MeV, but this assignment could not be made from the present work with any confidence. An experiment is planned to measure the angular distribution of these high-lying states at a somewhat higher bombarding energy in an effort to resolve some of these ambiguities.

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