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APPENDIX

The reduced width can be regarded as a product of two factors. Of these factors, the first is a measure of the probability that, in the initial nuclear state, all but one of the nucleons find themselves in an arrangement corresponding to the final state; the second factor measures the probability that, when this happens, the remaining nucleon appears as the reaction product.

The following equation gives the stripping reduced width as defined by Macfarlane and French[23] and modified for the present case:

$$\theta^2=\frac{d\sigma}{d\Omega}\left\{61.2\left[\frac{m+1}{m+2}\right]^2\left[\frac{2J_f+1}{2J_i+1}\right]\left(\frac{E_n}{E_d}\right)^{1/2}R^3\sigma_{\rm tab}\right\}^{-1}$$

where m is mass of target nucleus, J_i and J_f are the spins of the target and residual nucleus, respectively, E_d and E_n are the deuteron and neutron energies as determined in the rest frame of the target and residual nucleus, respectively, R is the interaction radius, and $\sigma_{\rm tab}$ is the angular distribution function tabulated in reference 15.

[23] M. H. Macfarlane and J. B. French, Rev. Mod. Phys. **32**, 567 (1960).

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Properties of F^{20}†

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The half-life of F^{20} is 11.36±0.07 sec. The thermal $F^{19}(n,\gamma)F^{20}$ cross section is 10.09±0.70 mb. Limits on the improbable decay modes of F^{20} were obtained.

BECAUSE of astrophysical applications and because of relevance to nuclear models, there has been, lately, interest in the $A=20$ nuclei.[1] We present our results for limits on improbable decay modes of 11-sec F^{20}, for the half-life of F^{20}, and for the thermal neutron capture cross section of F^{19}. In all our experiments, F^{20} was made by neutron capture in Teflon,[2] $(C_2F_4)_n$, in the 10^9/sec cm^2 thermal neutron flux density available at the 4-ft-thick graphite thermal column of the Pennsylvania State University 200-kW "swimming pool" reactor.

LIMITS ON IMPROBABLE DECAY MODES

A strong and constant F^{20} source was made by running with an electric motor a continuous 55-ft-long Teflon belt, 0.02 in. thick, $2\frac{1}{2}$ in. wide, through the slow neutron flux, out of the reactor pool water, past the counters, and back again. The usual decay proceeds[3,4] from the 2+ F^{20} by 5.42-MeV β^- emission to the 2+ 1.63-MeV state of Ne^{20}, and then to the 0+ ground state by 1.63-MeV γ emission.

We searched for the direct 7.05-MeV ground state β^- as follows: The beta spectrum of the belt was observed with a 3-in.-diameter, 2-in.-thick plastic phosphor,[5] a Dumont 6363 photomultiplier, a preamplifier, and a Radiation Counter Laboratories 128-channel analyzer. To reduce the background, a $\frac{1}{16}$-in.-thick sheet of plastic phosphor[5] was placed between the source and the 3 in. × 2 in. phosphor, and the multichannel analyzer was gated by pulses from the sheet. The background was thus reduced appreciably. The probability of γ interactions in the thin sheet was small, and those β rays that traveled in the correct direction were selected. The distance between the source and the $\frac{1}{16}$-in. sheet was 21 in., and the distance between the $\frac{1}{16}$-in.

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[1] J. A. Kuehner, Phys. Rev. **125**, 1650 (1962) and references therein.

[2] Teflon, grade 770M, was obtained from the Polymer Corporation of Pennsylvania, Reading, Pennsylvania.

[3] E. Freiberg and V. Soergel, Z. Physik **162**, 114 (1962).

[4] F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. **11**, 1 (1959).

[5] SC-700 Plastic Phosphor obtained from R.E.A.C., Crystals Division, Lynbrook, New York.

sheet and the 3 in. × 2 in. phosphor was 6 in.; the probability of summing pulses from a β ray and the associated γ ray was negligible.

There was, however, a high-energy background from the belt. The few fast neutrons present caused enough yield of the reaction $F^{19}(n,\alpha)N^{16}$ to make the 10.4-MeV β^- from 7.4-sec N^{16} troublesome. Since N^{16} decays faster than F^{20}, it was possible to reduce this difficulty by running the belt slowly. The optimum transit time from the thermal column to the counters was found to be 63 sec, since a longer time left too little F^{20} activity.

According to presently accepted assignments, the direct ground-state β transition is second forbidden nonunique, so that the precise shape of the spectrum is not known. If the spectrum has roughly the allowed shape, then, in about 0.08 of the ground-state transitions, the β-ray energy is between 5.42 and 7.05 MeV. The usual decay to the first excited state is allowed; it follows that, in 0.08 of the dominant decay, the β-ray energy is between 4.24 and 5.42 MeV. The ground-state branching ratio is, therefore, the number of beta counts between 5.42 and 7.05 MeV, divided by the number between 4.24 and 5.42 MeV. We obtain for this ratio 1/450.

We measured, with threshold detectors, the fast neutron flux density. If the spectrum is approximated by $\Phi_0 \exp(-0.58\ E\ \text{MeV}^{-1})$,[6,7] then $\Phi_0 = 4.4\times10^5$ neutrons/cm^2 sec MeV. Use of this value and the known $F^{19}(n,\alpha)N^{16}$ cross section[8] predicts that the above ratio should be 1/800 because of the N^{16} alone. This estimate has an uncertainty of a factor of 2 because the absolute cross sections that enter are not well known. Our result of 1/450 is therefore only an upper limit on the ground-state branching, and is no improvement on the result of $<1/3100$ obtained by Wong.[9]

To determine the intensities of transitions to the excited states of Ne^{20} above 1.63 MeV, a search for gamma rays from these states was made. The γ spectrum from the Teflon belt was obtained with a Harshaw 3-in-diameter, 3-in.-thick NaI(Tl) crystal, Dumont 6363 photomultiplier, and a Radiation Counter Laboratories 128-channel analyzer. The spectrum above 1.63 MeV was featureless except for the small high-energy peaks expected from the N^{16} contribution. It would be consistent to assign most of the observed high-energy γ counts to N^{16}; we treat them as an upper bound on the Ne^{20} γ-ray contribution as follows:

Let $n(E)$ be the number of counts recorded in the central channel of a photoelectric peak of energy E. Since the widths of photoelectric peaks as seen in scintillation counting are proportional to $E^{1/2}$, the number of counts in the photopeak is proportional to $n(E)E^{1/2}$. Let ϵ be the probability that a γ ray from the source interacts with the crystal, and let P be the photopeak-to-total ratio. Then the ratio of the number of γ rays of energy E to the number of energy 1.63 MeV is given by

$$N(E)/N(1.63) = (nE^{1/2}/\epsilon P)_E/(nE^{1/2}/\epsilon P)_{1.63}.$$

With the observed $n(E)$ and the values of ϵ and P given by Heath,[10] we obtain the results shown in Fig. 1.

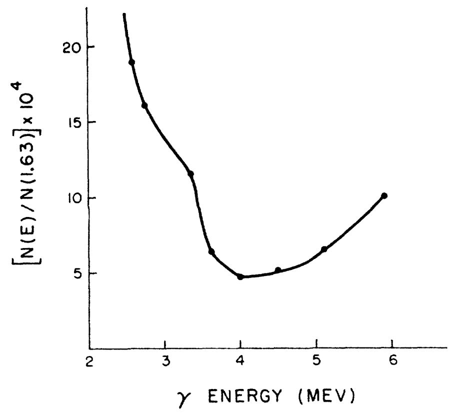

FIG. 1. Upper limit on the ratio of the number of γ rays of energy E, $N(E)$, to the number of γ rays of energy 1.63 MeV, $N(1.63)$, emitted after the β decay of F^{20}.

We now translate the observed upper limits on the β and γ intensities into lower limits on the log ft assignments of possible transitions. For the ground-state transitions, we use directly the observed 1/450. For the higher excited states, if nothing were known about the level assignments, we would have to add the upper limits of all possible cascades. We shall accept, however, the assignments given by Kuehner,[1] and observe that, in the de-excitation of each level, there is one γ ray that should occur with high probability. We can then take the upper limit on that γ ray alone. The results are given in Table I, with the energy of the γ ray from which the limit was assigned given in the fourth column. Previously, Wong[9] obtained >9.0 for the ground state, and Kavanagh[11] obtained >6.5 for the

TABLE I. The levels of F^{20}, the branching to these levels, and the log ft values for Ne^{20} β^- decay to these levels.

Level energy (MeV)	Spin and parity	β energy (MeV)	Dominant γ energy (MeV)	Branching to level	Log ft
7.02	(4−)	0.03	2.77	<0.0020	> −0.9
6.75	0+	0.30	5.12	<0.0067	> 3.0
5.80	1−	1.25	5.80	<0.0010	> 5.2
5.63	3−	1.42	4.00	<0.00048	> 5.8
4.97	2−	2.08	3.34	<0.0013	> 6.0
4.25	4+	2.80	2.62	<0.0019	> 6.6
1.63	2+	5.42	1.63	1.0	5.0
0	0+	7.05	···	<0.0022	> 8.2

[6] *Selected Reference Material*, U. S. Atomic Energy Program, Research Reactors (U. S. Government Printing Office, Washington, D. C., 1955), p. 108.

[7] S. S. Glickstein and R. G. Winter, Nucl. Instr. Methods **9**, 226 (1960).

[8] J. B. Marion and R. M. Brugger, Phys. Rev. **100**, 69 (1955).

[9] C. Wong, Phys. Rev. **95**, 761 (1954).

[10] R. L. Heath, U. S. Atomic Energy Commission Report IDO-16408, 1957 (unpublished).

[11] R. W. Kavanagh, Bull. Am. Phys. Soc. **3**, 316 (1958).

4.97-MeV level. All limits are consistent with, but no stringent test of, the currently accepted assignments.

HALF-LIFE OF F^{20}

Samples of Teflon were irradiated for 10 sec and then placed rapidly in front of a 3in.×3in. Harshaw NaI(Tl) crystal in a lead shield. The pulses were sent through a Hamner single-channel analyzer, set on the 1.63-MeV γ photopeak. The output of the analyzer was connected to a Hewlett Packard Model 523B Electronic Counter which pulsed a Hewlett Packard Digital Recorder. The number of counts per second was printed every other second.

The analyzer window was varied from 0.04 to 0.20 MeV. If other activities, with γ energy different from 1.63 MeV, were contributing, the apparent half-life would depend on the window width. No such change was observed.

A total of 35 runs was made. A half-life was calculated from each run through an IBM-650 least squares fit to the observed decay curve. The standard deviations of these separately obtained half-lives ranged from 0.06 to 0.24.

The 35 values for the half-life have a mean of 11.36 sec, and their distribution is consistent with a Gaussian of 0.20-sec standard error. If all errors were random, the standard error for the half-life would be 0.20 sec/$(35-1)^{1/2}=0.035$ sec. Several checks were made, and it appears that all electronic drifts were random. We cannot, however, exclude small systematic errors completely; we choose, as an estimate of our standard error, 0.07 sec, and obtain for the half-life of F^{20} 11.36 ± 0.07 sec. This result is slightly higher than the 11.2 ± 0.1 sec obtained by Scharff-Goldhaber, Goodman, and Silbert[12] and could lead to some decrease in the O^{20} half-life obtained by these authors.

THERMAL (n,γ) CROSS SECTION OF F^{19}

Teflon samples, 1in.×1in.×0.02in., with gold foils mounted on both sides, were irradiated for 5 min. The gold foils were removed and the Teflon was placed in a standard position in front of the same counting equipment used in the half-life measurements but with a 1/2-in. Al plate in front of the sample to remove the beta counts. All pulses higher than 0.02 MeV were accepted. The times of irradiations, removal, start of counting, and the weights of the samples were recorded. The experiment was done six times.

The thermal neutron activation cross section σ can be expressed as

$$\sigma=\frac{N_m\lambda e^{\lambda t_d}}{n_0\Phi_{\text{th}}E_f(1-e^{-\lambda t_e})(1-e^{-\lambda t_m})},$$

where N_m= number of counts recorded in time interval t_m, t_m= counting time, λ= disintegration constant, n_0 = number of target atoms, t_d= time interval between end of irradiation and start of counting, Φ_{th}= thermal neutron flux, t_e= irradiation time, and E_f= counter efficiency.

To determine the counter efficiency E_f, the same experiments were repeated three times with 1 in.×1 in. ×0.001 in. Al samples. The $Al^{27}(n,\gamma)Al^{28}$ thermal neutron cross section is $(241\pm3)\times10^{-27}$ cm^2.[13] The Al^{28} half-life is 136.2 ± 1.2 sec,[14] and Al^{28} emits a 1.78-MeV γ.[15] Solving the above equation for E_f and multiplying by 1.027,[10] the ratio of the counting efficiency for a 1.63-MeV γ to a 1.78-MeV γ in a 3 in.×3 in. NaI(Tl) crystal gives the counter efficiency for determining the cross section σ. The ratio of the Al to Teflon thermal flux was determined by counting the gold foils in a gas flow counter.

The results of the Teflon and Al irradiations yield for the F cross section $(10.0\pm0.7)\times10^{-27}$ cm^2. The standard error is the result of taking the square root of the sum of the squares of the errors in each term of the above cross section equation. Seren, Friedlander, and Turkel[16] previously reported for this cross section 9.4×10^{-27} cm^2 with a 20% probable error.

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[15] H. T. Motz and D. E. Alburger, Phys. Rev. **86**, 165 (1952).

[16] L. Seren, H. N. Friedlander, and S. H. Turkel, Phys. Rev. **72**, 888 (1947).