is a level at 2.34 Mev of the type $h_{9/2}$ which completely by-passes the metastable state and that there is a level at 2.75 Mev of the type $g_{9/2}$ which decays predominantly to the metastable state. The calculated curve is given in Fig. 2(b) as the solid line. The dashed curve shows the calculated cross section with the assumption that there is also an $f_{7/2}$ level (taken to be superimposed on the $h_{9/2}$ level for calculational simplicity since its exact location is not known) which by-passes the metastable state in its subsequent decay. It is seen that the experimental cross section is reasonably well represented by the calculated curves.

PHYSICAL REVIEW VOLUME 97, NUMBER 5 MARCH 1, 1955

Gamma Radiation from the Inelastic Scattering of Protons by F^{19}†

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(Received November 4, 1954)

The absolute cross section for the excitation of the 109-kev and 197-kev excited states of F^{19}, by the inelastic scattering of protons, has been studied as a function of bombarding energy up to 1750 kev by detecting the resultant gamma radiation in scintillation counters. Most of the resonances for the various $F^{19}(p,\alpha)O^{16}$ reactions appear as resonances for the excitation of one or both of these low-lying states. A detailed study of the angular distributions of the two gamma rays, together with the direct measurements of the lifetimes of these states by Thirion, Barnes, and Lauritsen, and the Coulomb excitation work of Sherr, Li, and Christy, leads to the assignments: 109-kev state, $J=\frac{1}{2}$, odd parity; 197-kev state, $J=5/2$, even parity. The nonresonant yield of 197-kev gamma rays is approximately that expected from Coulomb excitation at low incident proton energies. The nonresonant yield of 109-kev gamma rays exceeds the expected Coulomb excitation. In conjunction with the recent measurements of the elastic scattering of protons by F^{19} made by Peterson, Webb, Hagedorn, and Fowler, in this laboratory, and older measurements of the $F^{19}(p,\alpha)O^{16}$ reactions, the resonant inelastic cross sections allow a new determination of the partial widths for the various modes of decay of the Ne^{20} compound nuclear states.

I. INTRODUCTION

THE bombardment of F^{19} by protons up to energies $\sim$2 Mev can lead to the following reactions:

$$F^{19}+p\rightarrow Ne^{20*}\rightarrow \alpha_{0,\pi,1,2,3}+O^{16} \quad (1)$$

$$\rightarrow \gamma+Ne^{20} \quad (2)$$

$$\rightarrow p_0+F^{19} \quad \text{(elastic scattering)} \quad (3)$$

$$\rightarrow p_{1,2}+F^{19*} \quad \text{(inelastic scattering to first and second excited states of } F^{19}\text{)}. \quad (4)$$

The first of these reactions[1,2] can leave O^{16} in its ground state, in a pair-emitting state at 6.05-Mev excitation, or in gamma-ray emitting states at 6.13, 6.9, and 7.1 Mev. The detailed study of this reaction has made possible the assignment[2,3] of spin and parity to many of the levels in Ne^{20} and O^{16} involved in the reactions.

Reaction (2) shows resonances at proton energies of 669, 874, 935, 980, 1092, 1290, 1324, 1346, 1372, and 1422 kev.[2,4]‡ Elastic scattering of protons (reaction 3) has recently been investigated[5,6] up to 1.8 Mev and gives directly or confirms the spin and parity of many of the Ne^{20} states.

Prior to the present investigation, the inelastic scattering of protons by fluorine has been studied at 7.17-Mev and 8-Mev incident proton energy.[7] Several levels at energies >1.37 Mev in F^{19} were excited, but the resolution in these experiments was insufficient to resolve proton groups to the low-lying levels first reported by Mileikowsky and Whaling.[8] These levels have recently been excited by inelastic scattering of neutrons[9] and by inelastic scattering of α particles.[10,11]

† Assisted by the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.
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[1] Streib, Fowler, and Lauritsen, Phys. Rev. **59**, 253 (1941); Bennett, Bonner, Mandeville, and Watt, Phys. Rev. **70**, 882 (1946); Chao, Tollestrup, Fowler, and Lauritsen, Phys. Rev. **79**, 108 (1950).
[2] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952).
[3] W. A. Fowler and C. C. Lauritsen, Phys. Rev. **56**, 840 (1939); J. R. Oppenheimer and J. S. Schwinger, Phys. Rev. **56**, 1066 (1939); W. R. Arnold, Phys. Rev. **79**, 170 (1950); **80**, 34 (1950); Barnes, French, and Devons, Nature **166**, 145 (1950); C. Y. Chao, Phys. Rev. **80**, 1035 (1950); J. Seed and A. P. French, Phys. Rev. **88**, 1007 (1952); Rasmussen, Hornyak, Lauritsen, and Lauritsen, Phys. Rev. **77**, 617 (1950); Devons, Goldring, and Lindsey, Proc. Phys. Soc. (London) **A67**, 134 (1954).
[4] S. Devons and H. G. Hereward, Nature **162**, 331 (1948); R. M. Sinclair, Phys. Rev. **93**, 1083 (1954); T. M. Hahn and B. D. Kern, University of Kentucky report, August 31, 1954 (unpublished).
‡ See note added in proof in the caption of Fig. 1.
[5] Peterson, Barnes, Fowler, and Lauritsen, Phys. Rev. **94**, 1075 (1954).
[6] Webb, Hagedorn, Fowler, and Lauritsen, Phys. Rev. **96**, 851(A) (1954).
[7] Cowie, Heydenburg, and Phillips, Phys. Rev. **87**, 304 (1952); Arthur, Allen, Bender, Hausman, and McDole, Phys. Rev. **88**, 1291 (1952).
[8] C. Mileikowsky and W. Whaling, Phys. Rev. **88**, 1254 (1952).
[9] R. B. Day, Phys. Rev. **89**, 908(A) (1953).
[10] Sherr, Li, and Christy, Phys. Rev. **94**, 1076 (1954); **96**, 1258 (1954).
[11] N. P. Heydenburg and G. M. Temmer, Phys. Rev. **94**, 748(A) (1954) and Phys. Rev. **94**, 1232 (1954); G. A. Jones and D. H. Wilkinson (private communication).

A preliminary account of the excitation of these low-lying levels by protons has been published,[5] together with measurements of the lifetime of the states,[12] the α-particle Coulomb excitation cross section,[10] and a theoretical study of the various angular distributions.[13] On the basis of these results, the 109-kev state in F^{19} was assigned spin and parity $\frac{1}{2}^-$ and the 197-kev state $5/2^+$. The present paper contains a more detailed account of the studies of the 109-kev and 197-kev gamma rays excited by inelastic scattering of protons up to 1750-kev incident energy.

II. EXPERIMENTAL DETAILS

Protons were accelerated by the Kellogg Radiation Laboratory 2-Mv electrostatic accelerator and resolved in energy with a resolution of about one or two kev, in either electrostatic or magnetic analyzers. Proton beams of the order of $\frac{1}{2}$ μa bombarded thin evaporated targets of CaF_2 on 0.004-inch copper backings. The target chamber was a $2\frac{1}{2}$-inch o.d. Lucite cylinder of $\frac{1}{8}$ in. wall thickness with the proton beam entering normal to the axis of the chamber. The spot where the beam hit the target was accurately located on the chamber axis. It was possible to carry out angular distribution measurements of the emitted γ radiation by rotating a scintillation counter around the target at a fixed distance from the axis of the target chamber.

The scintillation counter employed a 1-in. diam $\times\frac{1}{2}$-in. thick NaI(Tl) crystal, drymounted in a thin aluminum housing coated on the inside with MgO. A $\frac{1}{4}$-inch thick quartz window let out the light from the scintillations. The mounted crystal was then cemented to a Dumont 6292 photomultiplier tube with Dow Corning high-viscosity silicone oil. The photomultiplier tube was magnetically shielded with a mumetal shield, and the crystal and photomultiplier were enclosed in an inner shield of mild steel, $\frac{1}{4}$ in. thick, and an outer lead shield, $\frac{1}{2}$ in. thick. The lead shield was found to be necessary to shield out x-radiation from the accelerator while the inner steel shield served the double purpose of supplying additional magnetic shielding for the photomultiplier tube, and of eliminating the fluorescent x-rays excited in the lead by γ radiation. The opening of the shielding towards the target was a collimator consisting of a $\frac{1}{4}$ in. thick lead ring backed by 2 mm of cadmium to remove the lead x-rays. The aperture of the collimator, $\frac{3}{4}$ in. diameter, defined the solid angle of the scintillation counter.

Typical differential bias curves taken with the arrangement are shown in Figs. 1(a), (b), and (c). The differences in the bias curves show clearly the variations in relative yield of the low-energy gamma rays and the 6- and 7-Mev gamma rays from one resonance to another. The small peak to the left of the main peak in Fig. 1(a) is probably the "escape" peak from the 109-kev peak,

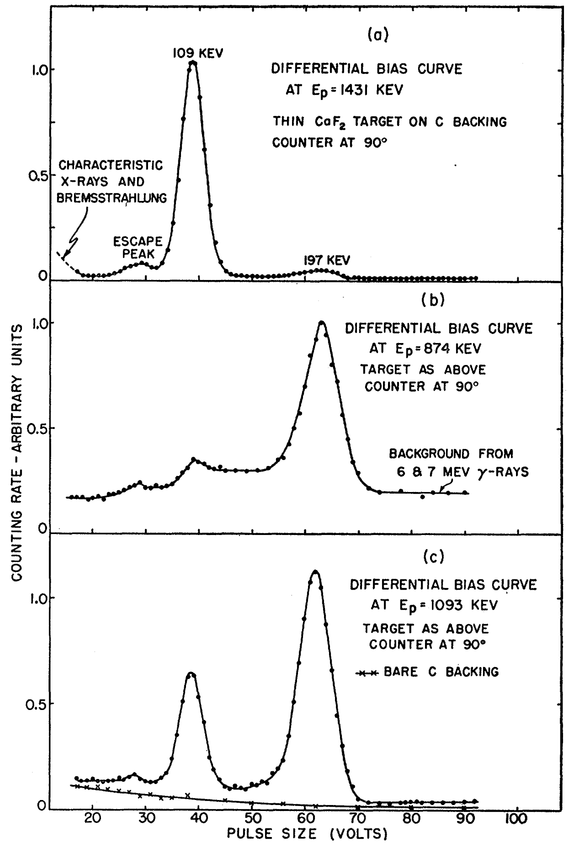

FIG. 1. Typical differential bias curves at the 1431, 873, and 1092-kev resonances in the $F^{19}+p$ reactions, showing the wide variations in relative yield of the various gamma radiations. *Note added in proof.*—The previously accepted resonance energies 1355, 1381, and 1431 have been changed to 1346, 1372, and 1422 kev on the basis of measurements made by the author during the past year. These measurements employed the 873.5-kev resonance in $F^{19}+p$ and the 1881.6 kev $Li^7(p,n)$ threshold as standards, and have an uncertainty of about 0.1 percent. The author is indebted to Mr. F. Mozer of this laboratory, and Dr. H. B. Willard of the Oak Ridge National Laboratory, for communicating their unpublished measurements of some of these resonance energies, which are in agreement with the results quoted here.

i.e., the peak due to photoelectric interactions in the NaI crystal in which the iodine K-x-ray escapes from the crystal. In some cases, the peak in this energy region may also contain a small contribution from residual fluorescence radiation from lead, and from the Compton collisions of the 197-kev radiation in the NaI crystal, in which the scattered quantum is scattered through angles near 180°. Similarly, a spurious contribution may appear near the 109-kev peak produced by back-scattering of the 197-kev radiation in the vicinity of the target. These effects determine the lower limit of detection for γ radiation near 109 kev and near 88 kev. The instrumental width at half-maximum of the 109-kev peak in Fig. 1(a) is about 14 percent in energy.

In most of the runs during these experiments, the number of counts was determined for a fixed quantity of proton charge collected by the target, as measured by a

[12] Thirion, Barnes, and Lauritsen, Phys. Rev. **94**, 1076 (1954).
[13] R. F. Christy, Phys. Rev. **94**, 1077 (1954).

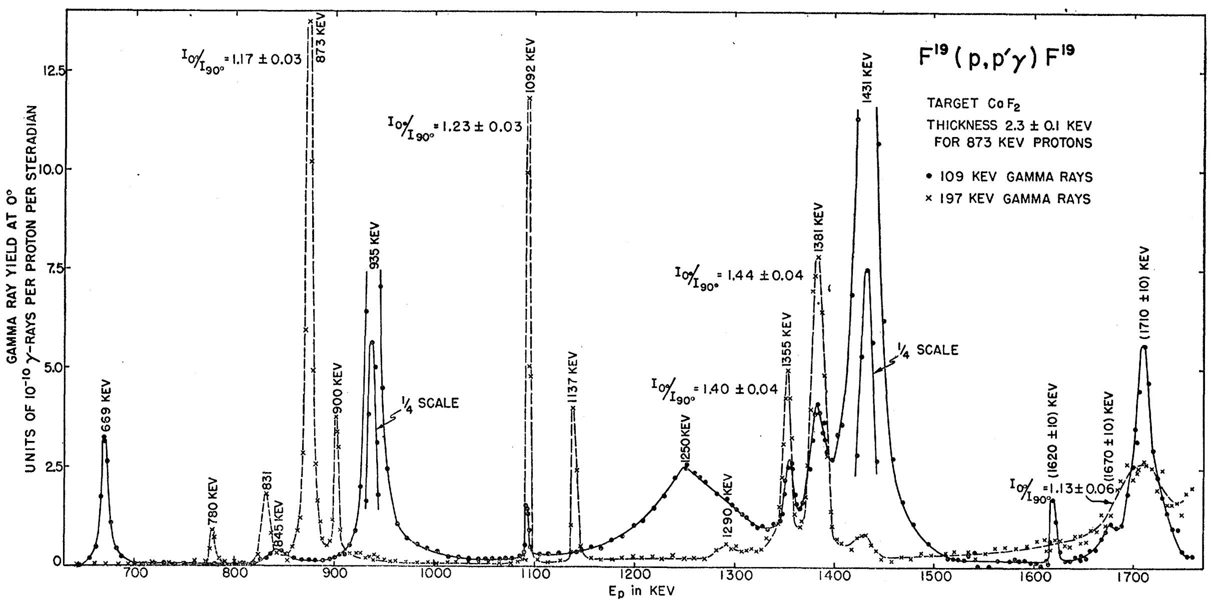

FIG. 2. Excitation curve for the 109-kev and 197-kev gamma rays from the inelastic scattering of protons by F^{19}. (See note added in proof, Fig. 1.)

calibrated current integrator. An electron suppressor was employed to remove extraneous electrons from the slits defining the incoming proton beam and the target was biassed at +300 volts with respect to its surroundings to prevent loss of secondary electrons.

III. EXCITATION ENERGY OF THE LOW-LYING F^{19} STATES

The energy scale of the scintillation counter was calibrated by observing the "photopeaks" from the Lu^{177} gamma rays at energies of (112.97±0.02) kev and (208.36±0.02) kev.[14] With this calibration, the quantum energies of the γ radiations were measured as (110±1) kev and (197.5±1.5) kev.[15] By the same method, Day has obtained the values (110±1) kev and (197±2) kev.[16]

Measurements of the excitation energies of these states in F^{19} have also been made by Peterson, Fowler, and Lauritsen,[3] by observing the difference in energy between the elastically and inelastically scattered protons from fluorine. These authors quote (108.8±0.8) kev and (196.0±1.4) kev.[17] Recently, Mills, Hilton, and Barnes[18] have observed the internal conversion electrons from these two states, and quote (109.1±1.0) kev and (196.8±1.5) kev. We take the weighted mean of these results as (109.2±0.6) kev and (196.8±0.7) kev. These values are in satisfactory agreement with determinations in other laboratories.[11,19]

From a comparison of many bias curves such as Fig. 1(a) and 1(c), we feel that the peak present at about 88 kev in Fig. 1(c) can be ascribed to the "escape" peak associated with the 109-kev peak. We estimate that the cascade transition through the 109-kev state occurs with less than 1 percent of the intensity of the 197-kev cross-over transition. Heydenburg and Temmer[11] estimate that the cascade transition occurs with <2 percent of the intensity of the 197-kev transition, while Jones *et al.*[19] estimate $<\frac{1}{2}$ percent.

Recently, Cook, Marion, and Bonner[20] have reported two levels in Ne^{19} at 255 and 289 kev respectively. It would be of special interest to ascertain the spin and parity of these Ne^{19} states to see if they correspond to the levels at 109 and 197 kev in F^{19}. No other gamma rays below 1.3 Mev have been observed in the $F^{19}(p,p')F^{19}$ reaction. It should be stated however, that the detection of weak low-energy radiation is made difficult by the x-rays and bremsstrahlung[21] from the target, and the presence of other, weakly-excited, states cannot be absolutely ruled out.

IV. EXCITATION CURVE OF THE 109-KEV AND 197-KEV γ RADIATION

The excitation curves of the radiations, following the inelastic proton scattering, are shown in Fig. 2. The most striking feature of these curves is the pronounced resonant character of the excitation. Most of the resonances which appear in Fig. 2 have been identified previously as resonances for the production of capture gamma radiation or for the emission of alpha particles to the ground state (α_0), to the pair-emitting state at 6.05

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[14] P. Marmier and F. Boehm, Phys. Rev. **97**, 103 (1955). The writer is indebted to these authors for the loan of a Lu^{177} source.

[15] The slightly higher values quoted in reference 5 appear to be in error because of a nonlinear amplifier gain characteristic curve.

[16] R. B. Day, (private communication).

[17] Peterson, Fowler, and Lauritsen, Phys. Rev. **96**, 1250 (1954).

[18] Mills, Hilton, and Barnes, Phys. Rev. (to be published).

[19] Jones, Phillips, Johnson, and Wilkinson (to be published).

[20] Cook, Marion, and Bonner (private communication to T. Lauritsen).

[21] Č. Zupančič and T. Huus, Phys. Rev. **94**, 205 (1954).

TABLE I. Cross sections and angular distributions for the gamma rays following inelastic scattering of protons by F^{19}. Cross sections quoted without parentheses are the sum of resonant and nonresonant values. Cross sections in parentheses are resonant portions only, when these are significantly different from the summed values.

Res. E (kev)	Γ (kev)	σ (109-kev γ's) mb	$I_{0°}/I_{90°}$ (109 kev γ's)	σ (197-kev γ's) mb	$I_{0°}/I_{90°}$ 197 kev γ's
669	7.5	20 ±3	0.98 ±0.02	(<0.2)	...
780	∼10[a]	(<0.2)	...	∼5	...
831	8.3	(<0.2)	...	∼8	...
845	23[a]	∼2	...	(<0.3)	...
873	5.2	(<0.3)	...	87 ±20	1.17±0.03
900	4.8	(<0.3)	...	∼20	...
935	8.0	147 ±22	0.98 ±0.02	(<1)	...
1092	<1.2	>13	0.98 ±0.03	>100	1.23±0.03
1137	3.7	(<0.4)	...	∼20	...
∼1250[a]	∼80[a]	17 ±3	1.01 ±0.03	1.7 ±0.5 (<1)	...
1290	19	(<1)	...	3 ±1 (1.5)	...
1346[a]	4.5[b]	17 ±4 (12)	0.99 ±0.03	27 ±7 (22)	1.40±0.04
1372[a]	15	26 ±4 (20)	1.00 ±0.03	40 ±6	1.44±0.04
1422[a]	14.6±1[a]	189 ±30	1.005±0.010	7 ±2 (≤3)	1.01±0.01
1610±10[a]	∼5[a]	12 ±3	...	(<2)	...
1660±10[a]	...	3	...	(≤2)	...
1700±10[a]	...	36 ±7	0.96 ±0.05	17 ±5	1.13±0.06
740	non-res. yield	0.1±0.04	1.01 ±0.05	0.14±0.05	1.4 ±0.2
1045	non-res. yield	1.0±0.04	0.96 ±0.05	0.3 ±0.1	1.2 ±0.1

[a] New measurements of widths or resonance energies in this investigation.
[b] D. Aaronson, Ph.D. thesis, University of British Columbia, 1952 (unpublished). T. Bonner and J. Evans, Phys. Rev. **73**, 666 (1948) quote 4.4 kev: Chao *et al.* (see reference 1) quote 8.6 kev.

Mev (α_π), or to the gamma-ray-emitting states of O^{16} at 6.13, 6.9, and 7.1 Mev (α_1, α_2, α_3, respectively).

The states of Ne^{20} which are believed to be of the type $J=1$, even (+) parity, formed by s-wave protons, decay predominantly to the 109-kev state of F^{19}. These states include the resonances at 669-kev, 935-kev,[3] and 1422-kev[5] proton energy. The 2^- (p-wave formation) state of Ne^{20}, corresponding to the 873.5-kev resonance, decays almost entirely to the 197-kev state of F^{19}, while the other 2^- states at resonance energies of 1346-kev and 1372-kev decay in comparable amounts to both low states of F^{19}. The very sharp 1092-kev resonance seems also to lead to comparable yields of the two excited states.

The structure of the excitation curve for the low-energy γ rays differs considerably from the excitation curve for the (p,α_{123}) reaction in the region of 1700 kev. The resonance at ∼845 kev is probably the same resonance as previously reported for emission of long-range α particles (α_0), and short range alphas (α_π). The small resonance at 780 kev is likely the same as that reported by Devons *et al.*[3] for nuclear pairs, and as observed in this laboratory,[22] for long-range α particles.

Table I gives a list of the resonances appearing in Fig. 2 with their cross sections. (See Sec. VI.) Except where noted, the resonance energies and widths are taken from Chao *et al.*[1] since no differences greater than the experimental resolution (∼1–2 kev) were observed between the widths and resonant energies of the low-energy and high-energy gamma rays.

[22] A. W. Schardt and W. A. Fowler (unpublished).

V. ANGULAR DISTRIBUTIONS

During the study of the excitation curves, readings of the yield were taken at both 0° and 90° with respect to the incident beam direction. At most resonances 45° and 135° intensities were also measured. At no energy was the 109-kev gamma radiation observed to be significantly anisotropic, whereas the 197-kev gamma radiation showed a distribution of the form $1+A\cos^2\theta$ with $A\geq 0$ at all energies covered in this investigation. The ratios $I_{0°}/I_{90°}$ are given in Table I for energies where angular distributions were measured.

The angular distribution of the gamma radiation may be readily evaluated from published formulas[23] if the distributions are calculated for separate j-values of the outgoing inelastic protons, and then combined incoherently.[13]

We assume $J=\frac{1}{2}$, even parity for F^{19} in its ground state.[24] If we assign $J=\frac{1}{2}$ to the F^{19} excited state, isotropy of the subsequent gamma radiation follows irrespective of the orbital and spin angular momenta in the earlier stages of the reaction. The consistent isotropy of the 109-kev radiation strongly suggests the assignment of $J=\frac{1}{2}$ for the 109-kev state, though isotropy of the radiation may also be caused in one of the earlier stages of the reaction.

For states of Ne^{20} with $J=2^-$, which can be formed by incoming p-wave protons with channel spin=1, we can calculate the expected angular distributions of the outgoing 197-kev radiation. If the F^{19} excited state has

[23] E.g., L. C. Biedenharn and M. E. Rose, Revs. Modern Phys. **25**, 729 (1953); or Sharp, Kennedy, Sears, and Hoyle, Chalk River Report CRT-556, 1953 (unpublished).
[24] A. P. French and J. O. Newton, Phys. Rev. **85**, 1041 (1952).

the assignment $J=5/2^+$, the radiation is of the $E2$ type, and is distributed as $(1+A\cos^2\theta)$ where $0.23\leq A\leq 0.75$, the limits corresponding to j-values of the outgoing proton of $\frac{3}{2}$ or $\frac{1}{2}$ respectively. $J=5/2^-$ for the F^{19} state would lead to isotropy of the inelastic protons since the F^{19} state could be reached from Ne^{20*} (2^-) by s-wave outgoing protons.[5] If the F^{19} excited state had the assignment $J=\frac{3}{2}^+$, it would be expected to decay by $M1$ radiation with a distribution of the form $(1+A\cos^2\theta)$ where $-0.45\leq A\leq 0$ which is clearly inconsistent with observation. It should be noted that $J=\frac{3}{2}^+$ for the F^{19} state, followed by $E2$ radiation, could give $0\leq A\leq 0.6$. This possibility is discussed later in Sec. VII. $J=\frac{3}{2}^-$, and $J\geq 7/2$ for the 197-kev state are not considered here because of lifetime considerations (discussed in Sec. VII).

It is interesting to note that the long lifetime of the 197-kev state, $\sim 10^{-7}$ sec, allows an appreciable decrease of the initial anisotropy of this state due to magnetic or electric interactions of extra-nuclear fields on the excited F^{19} nucleus. If the minimum value of A observed, 0.17, corresponds to the minimum A allowed for $J=5/2^+$ in the excited state, namely 0.23, it would appear that the anisotropy has been reduced to $\sim 7/10$ of the predicted value. This attenuation of the anisotropy is consistent with that obtained in the Coulomb excitation work,[10] and in the γ–γ correlation[19] following the β decay of O^{19}.

VI. ABSOLUTE CROSS SECTIONS

In addition to the gamma-ray yield, and the geometrical and intrinsic efficiency of the scintillation counter, the calculation of absolute cross sections requires a knowledge of the stopping cross section, ϵ, of the target material per fluorine nucleus. The value of ϵ for calcium was estimated from the known ϵ for argon as a function of energy.[25] ϵ for fluorine was interpolated from the values for oxygen and neon. Values of ϵ for fluorine determined experimentally by T. Webb and W. A. Fowler in this laboratory differ from this interpolation by only a few percent over the range of energies of the present experiment. We therefore estimate the uncertainty in ϵ for CaF_2 as less than 10 percent.

The target thickness was determined in a separate experiment on the 6- and 7-Mev gamma rays by comparing the area under the thin-target yield curve at the 873-kev resonance with the yield of a thick target. This method[26] is independent of the energy inhomogeneity of the incoming proton beam. The target employed was found to be (2.3 ± 0.1) kev thick for 873-kev protons.

The calculation of the intrinsic efficiency of the scintillation counter involves only the well-known cross sections for the photoelectric and Compton interactions of the gamma rays in the NaI crystal. Small corrections of the order of 2–6 percent were made for the "escape peaks" and for the absorption of Compton scattered quanta in the crystal which gave pulses in the full energy peak of the bias curve.

The geometrical efficiency, or solid angle calculation, involves the absorption cross section of the two gamma rays in the lead and cadmium of the collimator. We consider the resulting efficiency of the counter is accurate to better than 10 percent.

The absolute cross section for the 109-kev radiation was obtained at the 669-kev resonance from the height of the step in the excitation curve for a thick CaF_2 target of compressed powder. The cross sections at other resonances were then determined by comparing the maximum resonant yields at the peaks of the resonances using the thin target. Small corrections were made for the fact that at some narrow resonances the target thickness was an appreciable fraction of the natural width of the resonance. Corrections were also made for the change in ϵ with bombarding energy

The ratio of the peak yields of resonances will vary if the energy inhomogeneity of the beam is an appreciable fraction of the natural width of the resonance and is variable. In these measurements the ratios of peak yields were reproducible to ± 10 percent or better for varying conditions of beam resolution, focussing, etc. We conclude that our beam resolution is sufficient that it contributes little to the error in peak yield ratios except perhaps for the sharpest resonances listed. Considering all the sources of error, we have assigned probable errors to the absolute cross sections varying from 15 to 25 percent depending on the reproducibility of the experimental data and the accuracy with which the "photopeaks" in the bias curve could be separated from the continuum of pulse sizes due to background effects in the crystal.

Peterson, Fowler, and Lauritsen[17] have measured the absolute cross sections for the inelastic scattering by detecting the inelastically scattered protons in a magnetic spectrometer. These authors calibrated their spectrometer solid angle by observing Rutherford-scattered protons from copper. At $E_p=1422$ kev they give σ(109-kev state)$=(187\pm 15)$ mb, and σ(197-kev state)$=(7\pm 2)$ mb. These values are to be compared with the values, σ(109-kev state)$=(189\pm 30)$ mb and σ(197-kev state)$=(7\pm 2)$ mb, from the present investigation. Similarly, their value σ(197-kev state)$=(42.7\pm 4.0)$ mb at the 1372-kev resonance is in good agreement with the value σ(197-kev state)$=(40\pm 6)$ mb of the present investigation.

It is of interest to compare the nonresonant cross sections listed in Table I at 740- and 1045-kev proton energy with the values expected from Coulomb excitation of these states by protons. As we show in Sec. VII, we take the assignments of the two excited states to be: 109 kev, $\frac{1}{2}^-$; 197 kev, $5/2^+$.

Employing the terminology of Bohr and Mottelson,[27]

[25] Reynolds, Dunbar, Wenzel, and Whaling, Phys. Rev. **92**, 742 (1953); Chilton, Cooper, and Harris, Phys. Rev. **93**, 413 (1954).

[26] Bernet, Herb, and Parkinson, Phys. Rev. **54**, 398 (1938); Fowler, Lauritsen, and Lauritsen, Revs. Modern Phys. **20**, 236 (1948).

[27] A. Bohr and B. R. Mottelson, Kgl. Videnskab. Selskab, Mat.-fys. Medd. **27**, No. 16, (1953).

we can express the cross section for $E2$ excitation of a 5/2 level as

$$\sigma=\frac{2\pi^2}{25}\frac{1}{Z_2^2e^2}\left(\frac{Mv_f}{\hbar}\right)^2 B_{E2(\frac{1}{2}\rightarrow\frac{5}{2})}g_{E2}(\xi),$$

where $Z_2=9$ for F^{19}, M is the proton mass, v_f is the velocity of the outgoing proton, and $g(\xi)$ is a function of the velocities and charges of the nuclei involved which has been calculated by Alder and Winther.[28] We have taken $\xi=n_2-n_1$ where $n_1=Z_1Z_2e^2/\hbar v_i$ and $n_2=Z_1Z_2e^2/\hbar v_f$.

If we take the value of $B_{E2(\frac{1}{2}\rightarrow\frac{5}{2})}$ from the directly measured lifetime of $\sim10^{-7}$ sec for the 5/2 state of F^{19}, we have $B_{E2(\frac{1}{2}\rightarrow\frac{5}{2})}=3B_{E2(\frac{5}{2}\rightarrow\frac{1}{2})}=2.0\times10^{-69}$. The calculated cross sections are 1.4×10^{-28} cm^2 at 740-kev incident energy, and 2.9×10^{-28} cm^2 at 1045-kev proton energy. These are in good agreement with the observed values, namely $(1.4\pm0.5)\times10^{-28}$ cm^2 and $(3\pm1)\times10^{-28}$ cm^2.

Similarly we calculate the cross sections for $E1$ excitation of a $\frac{1}{2}^-$ state from the formula[28]

$$\sigma=\frac{2\pi^2}{9\hbar^2}\frac{Z_1^2e^2}{v_i^2}B_{E1(\frac{1}{2}\rightarrow\frac{1}{2})}g_{E1}(\xi).$$

Employing the B calculated from the observed lifetime of $\sim10^{-9}$ sec, we have $\sigma=7\times10^{-30}$ cm^2 at 740 kev, and $\sigma=9\times10^{-30}$ cm^2 at 1045 kev. These values are clearly much smaller than the experimentally observed values of $(1\pm0.4)\times10^{-28}$ cm^2 and $(1\pm0.4)\times10^{-27}$ cm^2 respectively.

These large values observed for the excitation cross section of the 109-kev state, may be attributed to the formation of very broad 0^+ states of Ne^{20}, which can decay by p-wave proton emission to the $\frac{1}{2}^-$ state but would require d-wave proton emission to decay to the 197-kev state.

If the excitation of the 197-kev state at 740 kev, and 1045-kev proton energy proceeds mainly by Coulomb excitation, the angular distribution of the gamma radiation may be predicted. The $I_{0°}/I_{90°}$ ratios calculated for the 197-kev excitation are 1.28 and 1.25 respectively. If there is some attenuation of the anisotropy due to lifetime effects (see Sec. V), these ratios should be reduced to about 1.19 and 1.17. While these values are not inconsistent with those of Table I, the experimental ratios are not sufficiently accurate to justify any conclusions.

The isotropy of the 109-kev radiation at 740 and 1045 kev is consistent with the suggested assignment of $J=\frac{1}{2}$ to this state. Further work is in progress to measure the cross sections and angular distributions of the nonresonant gamma radiation as a function of energy.

[28] K. Alder and A. Winther, Phys. Rev. **91**, 1578 (1953); **96**, 237 (1954).

VII. SPIN AND PARITY OF THE LOW LYING STATES OF F^{19}

In our earlier series of papers on the assignment of spin and parity to the F^{19} states[5,10,12,13] we suggested the assignments of spin $\frac{1}{2}^-$ and $5/2^+$ for the 109-kev and 197-kev states, respectively. In this section of the present paper we shall merely review the arguments for the sake of completeness. A similar discussion is given in a paper by Sherr, Li, and Christy.[10]

The experimental data on which the assignments were based include:

(a) The excitation function of the radiation from inelastic proton scattering.

(b) The angular distribution of the inelastically scattered protons.

(c) The angular distribution of the 109 and 197 kev gamma radiation.

(d) The mean lifetime[12] of the gamma rays: 109 kev, $\sim10^{-9}$ sec; 197 kev, $\sim10^{-7}$ sec; 88 kev, $\gtrsim10^{-5}$ sec.

(e) The transition probability for the 109-kev and 197-kev transition as determined from Coulomb excitation by α particles.[10]

(f) The angular distribution of the Coulomb-excited gamma radiation.[10]

The directly measured lifetimes immediately suggest that the multipolarities of the gamma-ray transitions are limited as follows:

197 kev—not higher than $E2$;

109 kev—not higher than $M1$ or $E1$;

88 kev—not lower than $E2$.

Taking the ground state of F^{19} as $\frac{1}{2}^+$, we are then lead to the possible assignments: 197-kev state, $5/2^+$, $\frac{3}{2}\pm$, $\frac{1}{2}\pm$; 109-kev state, $\frac{3}{2}\pm$, $\frac{1}{2}\pm$. The $\frac{1}{2}\pm$ and $\frac{3}{2}\pm$ assignments for the 197-kev state would be expected to lead to $M1$ or $E1$ radiation which would be several orders of magnitude faster than the observed transition and would thus require to be forbidden by an improbably large factor, $\geq10^4$. In addition, the angular distribution of the 197-kev gamma radiation requires $E2$ de-excitation in both the proton and α particle experiments. Furthermore $\frac{1}{2}\pm$, $\frac{3}{2}\pm$ assignments to the 197-kev state would allow the 88-kev transition to a $\frac{1}{2}$ or $\frac{3}{2}$ state at 109 kev to be $E1$ or $M1$, requiring that the 88-kev gamma-ray transition probability also be reduced by a factor $\geq10^4$. In view of these limitations, we consider the assignment $5/2^+$ to be the only reasonable assignment to the 197-kev state. A comparison of the observed lifetime and the cross section for Coulomb excitation by α particles,[10] also leads directly to an $E2$ assignment for both excitation and de-excitation of this level, further strengthening the $5/2^+$ assignment.

Of the possible assignments for the 109-kev state, the $\frac{1}{2}$ assignment is suggested by the isotropy of the 109-kev gamma ray in both the proton and α particle work. $\frac{3}{2}\pm$ would require the reduction of the $M1$ or $E1$ 88-kev transition probability from the $5/2^+$ state by an im-

TABLE II. Partial widths of certain $F^{19}+p$ resonances below 1650-kev proton energy. All Γ's in laboratory coordinates. $[\Gamma_{c.m.}=(19/20)\Gamma_{lab}]$. A dash indicates not observed—no upper limit available. An x indicates not observed—forbidden by J and π considerations.

E_{res} (kev)[a]	$Ne^{20*}J,\pi$	Γ (kev)[a]	Γ_{p_0} (ev)	Γ_{p_1} (ev)	Γ_{p_2} (ev)	Γ_{α_0} (ev)	Γ_{α_π} (ev)	Γ_{α_1} (ev)	Γ_{α_2} (ev)	Γ_{α_3} (ev)	$\Gamma_{12\ Mev}$ γ's (ev)
340	1, +[b]	2.9[j]	45	<0.5	<0.1	x	x	2800	16	75	≤1.6[c]
669	1, +[d]	7.5	7300	46	<0.5	x	x	110	0.4	25	2.4[e]
935	1, +[d]	8.0	1400	3000	<20	x	x	2800	100	780	~1,[f] ≤1.8[c]
1422	1, +[g]	14.6	12 400	2200	≤35	x	x		total <40		4.5[e]
598	2, −[h]	37	43	<500	<500	x	x	37 000	<100	<100	<21[c]
873	2, −[d]	5.2	1100	<2	570	x	x	2400	850	300	~1,[f] ≤1.9[c]
1346	2, −[g]	4.5	300	300	600	x	x	1800[i]	450[i]	1050[i]	≤2[c]
1372	2, −[g]	15	2500	700	1400	x	x	9100	840	520	~3,[f] ≤8[c]
483[j]		2.2[j]	~11/ω	<1.5	<1.5	—	—	~1700	~30	~450	—
720[k]		~30	~2/ω	<10 000	<10 000	~20 000	~10 000	—	—	—	—
780[k]		~10	~14/ω	<400	~9000	~400	~50	—	—	—	—
831		8.3	~65/ω	<6	~2300	—	—		total ~5400		—
843	(0, +)[l]	23	~23 000	~50	<10	~5	~33	—	—	—	—
900		4.8	~65/ω	<30	~2200	—	—	~2500	<130		—
1137		3.7	~50/ω	<40	~2100	—	—		total ~1600		—
~1250		~80	~700/ω	~70 000	<4000	—	~10 000	—	—	—	—
1290	(3, +)[m]	19	~150	<600	~900	—	—	~13 000	~1300	~3200	—

[a] Resonance widths, energies, from Table I. α_1, α_2, α_3 data from Chao *et al.*, reference 1; J. M. Freeman, Phil. Mag. **41**, 1225 (1950); Seed and French, reference 3; and Peterson *et al.*, reference 17.
[b] Barnes *et al.*, Arnold, reference 3.
[c] A. B. Clegg (private communication).
[d] Seed and French, reference 3.
[e] Sinclair, reference 4, cross sections corrected to $(p,\alpha\gamma)$ cross sections of Chao *et al.*[1]
[f] Hahn and Kern, reference 4.
[g] References 5, 6, 2.
[h] Seed and Dearnley, quoted by D. H. Wilkinson and A. B. Clegg (private communication).
[i] (p,α) cross section measured by comparison with 1372-kev resonance cross section.
[j] S. E. Hunt, Proc. Phys. Soc. (London) **A65**, 982 (1952).
[k] $(p,\alpha\pi)$ cross sections estimated from 843-kev cross section of Chao *et al.*[1] and excitation function of Devons *et al.*, reference 3. (p,α_0) from unpublished work of A. W. Schardt and W. A. Fowler.
[l] From elastic scattering.
[m] Chao, reference 3.

probably large factor, $\geq 10^4$. An assignment of $\frac{1}{2}^+$ to the 109-kev state would mean that the $E2$ transition from the 197- to the 109-kev state would be expected to have a lifetime $\approx(197/88)^5\times10^{-7}\approx5\times10^{-6}$ sec. While this is below the lower limit observed experimentally for the 88-kev transition lifetime, a stronger argument against the $\frac{1}{2}^+$ assignment comes from combining the knowledge of the lifetime of the 109-kev state with the Coulomb excitation cross section of Sherr, Li, and Christy.[10] If the Coulomb excitation is assumed to be $M1$, then the observed absolute cross section predicts a lifetime of the order of 10^{-12} sec, as compared with the observed lifetime of 10^{-9} sec. $E1$ excitation, on the other hand, yields good agreement between the measured and predicted lifetimes.

We therefore conclude that the most reasonable explanation of the experimental results cited, is the assignment, 109-kev state, $\frac{1}{2}^-$; 197-kev state, $5/2^+$. Since the publication of our earlier papers, an independent check of these assignments has been made.

Jones, Phillips, Johnson, and Wilkinson[19] have reexamined the β decay of Ne^{19} and O^{19} in detail, and they have also studied the α-particle Coulomb excitation of F^{19}. The F^{19} assignments which they conclude are necessary to explain their results, are in agreement with our work.

The occurrence of a $5/2^+$ state is not too surprising for this nucleus as some, or all, of the nucleons outside the O^{16} core are probably in $d_{\frac{5}{2}}$ orbits. It has been pointed out that the ground state magnetic moment may be explained as well by the $(d_{\frac{5}{2}}{}^3)_{\frac{1}{2}}$ assignment as by the more usual assignment $2s_{\frac{1}{2}}$.

At first sight the occurrence of an odd parity state, so close as 109 kev to the ground state, might seem a little surprising. It has been pointed out by Christy and Fowler[29] that the $\frac{1}{2}^-$ state may be considered as a hole in the $p_{\frac{1}{2}}$ shell with the four nucleons outside the p-shell being coupled to give $T=J=0$. From empirical mass considerations it can be shown that the strong binding of the four outside nucleons compensates in large measure for the energy required to make a hole in the p shell.

VIII. COMPETING MODES OF DECAY OF THE Ne^{20} COMPOUND NUCLEUS

On the basis of the known (p,α) cross sections, Chao *et al.*[1] made an analysis of the $F^{19}+p$ resonances into partial widths. Since their analysis, the following new data have become available: (i) the inelastic scattering cross sections of the present paper; (ii) J and parity values for many of the resonances; (iii) radiative capture cross sections; (iv) elastic scattering studies.[30] A recalculation of partial widths incorporating the new

[29] R. F. Christy and W. A. Fowler, Phys. Rev. **96**, 851(A) (1954).

[30] The writer is indebted to Webb, Hagedorn, Fowler, and Lauritsen, for communicating their experimental results to him before publication. The writer is also indebted to E. Baranger for discussions of her calculations based on the elastic scattering data.

data is presented in Table II. The (p,α) reaction data is taken from Chao *et al.*[1] except where noted.

If Γ_R is the total partial width for all reactions except elastic scattering, and Γ_{p0} is the partial width for re-emission of the incident proton, we can write the Breit-Wigner dispersion formula for the cross section at resonance in the form

$$\sigma_{\text{Reaction}} = 4\pi\lambda\!\!\!^{-2}\omega\Gamma_{p0}\Gamma_R/\Gamma^2,$$

where

$$\omega = (2J+1)/(2s+1)(2i+1).$$

J is the total angular momentum of the compound nucleus, and s and i are the intrinsic spin of the incoming particle (proton), and the total angular momentum of the target nucleus respectively. $\Gamma(=\Gamma_{p0}+\Gamma_R)$ is the resonance width, a directly measured quantity. If ω is known, the measurement of σ_{Reaction} and Γ leads to two sets of values of Γ_{p0} and Γ_R. The study of the elastic scattering will remove the ambiguity, in general, since the magnitude of the scattering anomaly, due to the interference of resonant and Rutherford scattering, depends on Γ_{p0}/Γ. Where the elastic scattering does not show an appreciable anomaly, we have taken the smaller of the two possible values of Γ_{p0}/Γ as being correct. In the case of narrow resonances such as the 1092-kev resonance, it is possible that an elastic scattering interference anomaly might have been missed due to the averaging produced by the finite experimental resolution. On the other hand, resonances several hundred kev wide would give rise to such broad elastic scattering anomalies that the identification of the anomalies would become difficult.

It should be pointed out that there is considerable divergence in the published literature on the cross-section values for the (p,α) reactions, particularly for the (p,α_π) and (p,α_0) resonances. The partial widths for these processes in Table II are subject to corresponding uncertainties, which may be as high as a factor 3 for the (p,α_π) and (p,α_0) partial widths.

Known $(p,\alpha_{1,2,3})$ resonances at 222, 486, 1092, and 1176 kev, (p,α_π) resonances at 1130 and 1367 kev, (p,α_0) resonances at 1100 and 1380, and (p,γ) resonances at 980, and 1324 have been omitted from Table II, due to lack of knowledge regarding widths, cross sections, and competing modes of decay. In addition we have not included the region near 1700 kev as there are several $(p,\alpha_{1,2,3})$, (p,α_0), and (p,α_π) resonances close together in energy, and the inelastic scattering and elastic scattering data are not subject to clear interpretation.

The resonance at 1610 kev appears to decay entirely by emitting inelastic protons to the 109-kev state. If it is true that no other reaction takes place at this resonance, an assignment of $J=0$, odd parity, would seem to be indicated for the state of Ne involved. Further investigation of this region, for the emission of alpha particles, is in progress.

Little can be said at our present stage of knowledge regarding the observed partial widths listed in Table II. The first half of the table concerns the resonances for which J and parity (π) are known, and these resonances form a reasonably consistent set.

The earlier failure to observe capture radiation at 935 kev and 340 kev finds a natural explanation in the small value of Γ_{p0}/Γ, which enters the expression for the resonant cross section for radiative capture. The close spacing of levels in F^{20} in the energy region corresponding to the present energy region in Ne^{20}, indicates that there are many $T=1$ states present. It may be that the small widths for α emission of the 1422-kev $(1,^+)$ and the 843-kev $(0,^+)$ states are due to this cause. Wilkinson and Clegg (Table II, reference h) have suggested that the low yield of $E1$ capture gamma rays at 598 kev and 873 kev, brands these as $T=0$ levels. The same argument applies to the 1346- and 1372-kev (2^-) levels, although small radiative widths for these four levels can arise from other causes. The small α_0 and α_π width of the 780-kev resonance would be consistent with either a $T=1$ assignment or a high value of J. The preference of this state for inelastic scattering to the $5/2^+$ state of F^{19} indicates that the latter alternative is probably correct. It seems probable that all the observed (p,α_0) resonances have $T=1$ and/or high J values, since the resonances would probably be so broad as to be unobserved in the absence of some inhibiting factor.

E. Baranger has computed reduced widths for the resonances with known J-values, and these will be included in a forthcoming publication.

IX. ACKNOWLEDGMENTS

It is a pleasure to acknowledge my indebtedness to C. C. Lauritsen, W. A. Fowler, R. F. Christy, R. Sherr, and T. Lauritsen for assistance in the experimental work and many helpful discussions of the data. The writer is also indebted to the California Institute of Technology for the award of a Research Fellowship, and to the University of British Columbia for granting leave of absence.