Resonances in the Disintegration of Fluorine by Protons

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The voltage regulation of the Rice Institute pressure electrostatic generator has been improved by the use of a modulated electron current which proceeds up the vacuum tube in the opposite direction to the positive ions. The auxiliary apparatus is composed of a magnetic voltage analyzer and an electronic potential regulator. Calculations indicate that at 1 Mev the potential is controlled to ± 150 volts. The resonances in the production of gamma-rays and soft radiation (pairs) when F^{19} is bombarded by protons have been studied with proton energies of from 800 to 1400 kev. Resonances for the emission of gamma-rays have been observed at 820, 862, 890, 927, 1076, 1107, 1122, 1161, 1274, 1335, and 1363 kev. The experimental half-widths of these resonance levels vary from 1.9 to 50 kev. Resonances for the production of soft radiation (pairs) have been observed at 832, 1100, 1220, and 1362 kev; the widths of these resonance levels vary from 28 to 85 kev. An explanation of the varying intensities and widths of the levels can be made on the basis that the protons which produce the disintegrations and the alpha-particles which result have several different values of angular momentum.

INTRODUCTION

The transmutation of fluorine by protons has been the subject of extensive experimental and theoretical interest since the pioneer experiments of Cockcroft and Walton in 1932. Alpha-particles were the first products of the disintegration of fluorine which were detected.[1] These alpha-particles have been studied by Oliphant and Rutherford,[2] by Henderson, Livingston, and Lawrence,[3] and more recently by Burcham and Smith.[4] From these experiments it is known that the 5.9-cm alpha-particles come from the following reaction:

$$_9F^{19}+{}_1H^1\rightarrow{}^*{}_{10}Ne^{20}\rightarrow{}_8O^{16}+{}_2He^4+7.95\text{ Mev.} \quad (1)$$

The Q value of 7.95 Mev has been accurately determined by Burcham and Smith.[4] The early excitation curves for these alpha-particles gave a continuous increase in the yield in the proton energy range of from 700 to 1500 kev.[3] In 1939 Burcham and Devons[5] found resonances in the excitation curve at 720 and 830 kev. Streib, Fowler, and Lauritsen[6] extended these measurements to 1500 kev and found additional resonances at 1140 and 1350 kev.

Intense gamma-radiation was the next product of the disintegration of fluorine which was observed. These first experiments were carried out by McMillan[7] in 1934. A large amount of work has been done to determine the quantum energy of this radiation accurately.[8] The latest experiments with the cloud-chamber technique which have been carried out by Lauritsen, Lauritsen, and Fowler[9] give a value of 6.2 Mev for this energy, while the experiments of Dee, Curran, and Strothers[10] with a magnetic spectrograph give a value of 6.5 Mev.

Hafstad, Heydenburg, and Tuve[11] discovered pronounced resonances in the production of gamma-rays when fluorine is bombarded by protons. Later experiments[12–14] and especially

[1] J. D. Cockcroft and E. T. S. Walton, Proc. Roy. Soc. **A137**, 229 (1932).
[2] M. L. E. Oliphant and Lord Rutherford, Proc. Roy. Soc. **A141**, 259 (1933).
[3] M. C. Henderson, M. S. Livingston, and E. O. Lawrence, Phys. Rev. **46**, 38 (1934).
[4] W. E. Burcham and C. L. Smith, Proc. Roy. Soc. **A166**, 176 (1938).
[5] W. E. Burcham and S. Devons, Proc. Roy. Soc. **A173**, 555 (1939).
[6] J. F. Streib, W. A. Fowler, and C. C. Lauritsen, Phys. Rev. **59**, 253 (1941).
[7] E. McMillan, Phys. Rev. **46**, 325; 868 (1934).
[8] H. R. Crane, L. A. Delsasso, W. A. Fowler, and C. C. Lauritsen, Phys. Rev. **46**, 531 (1934); L. A. Delsasso, W. A. Fowler, and C. C. Lauritsen, Phys. Rev. **51**, 391; 527 (1937); E. R. Gaerttner and H. R. Crane, Phys. Rev. **52**, 582 (1937).
[9] T. Lauritsen, C. C. Lauritsen, and W. A. Fowler, Phys. Rev. **59**, 241 (1941).
[10] P. I. Dee, S. C. Curran, and J. E. Strothers, Nature **143**, 759 (1939).
[11] L. R. Hafstad, N. P. Heydenburg, and M. A. Tuve, Phys. Rev. **49**, 866 (1936); **50**, 504 (1936).
[12] R. G. Herb, D. W. Kerst, and J. L. McKibben, Phys. Rev. **51**, 691 (1937).
[13] S. C. Curran, P. I. Dee, and V. Petrzilka, Proc. Roy. Soc. **A169**, 269 (1938).
[14] E. J. Bernet, R. G. Herb, and D. B. Parkinson, Phys. Rev. **54**, 398 (1938).

those of Bernet, Herb, and Parkinson showed that the resonances were quite sharp. The experimental half-widths of the resonances were found by Bernet, Herb, and Parkinson to vary from 10 to 20 kev. Later, the low energy part of the excitation curve was investigated carefully by Burcham and Devons.[5] They were able to reduce the observed half-widths of the resonances at 330 and 670 kev to 6 kev. Bennett, Bonner, Hudspeth, and Watt[15] reduced the experimental half-widths of the resonances at 862 and 927 kev to 8 and 9 kev, respectively. These widths were in most cases believed to be experimental and not the natural widths of the resonance levels.

The nuclear reaction which was proposed originally to explain the origin of the gamma-radiation was the following:

$$_9F^{19}+{_1H^1}\rightarrow{^*_{10}Ne^{20}}\rightarrow{_{10}Ne^{20}}+\gamma+13.1\text{ Mev.} \quad (2)$$

For several years this reaction was believed to be the correct one, primarily because it was thought that sharp resonances would be observed only in the capture type disintegration of reaction (2). Since the quantum energy of the gamma-rays was known to be nearly half the Q value of reaction (2), it was generally believed that two gamma-rays were emitted in cascade from the excited $_{10}Ne^{20}$ nucleus. However in 1939 the experiments of Dee, Curran, and Strothers[10] to detect the simultaneous emission of two quanta showed that less than 1 percent of the gamma-rays were produced simultaneously. This showed that reaction (2) is not the source of the gamma-radiation which is observed.

The nuclear reaction, now generally accepted, which explains the origin of the gamma-rays is the following:

$$\begin{array}{c} _9F^{19}+{_1H^1}\rightarrow{^*_{10}Ne^{20}}\rightarrow{^*_8O^{16}}+{_2He^4}+Q_3, \\ ^*_8O^{16}\rightarrow{_8O^{16}}+\gamma. \end{array} \quad (3)$$

According to this reaction the gamma-rays accompany the emission of a short range alpha-particle. These short range alpha-particles were first observed by McLean, Becker, Fowler, and Lauritsen[16] in 1939. From the 0.86-cm range of the alpha-particles they calculated that the Q value of reaction (3) is 1.74 Mev. They also showed that these short range alpha-particles displayed a resonance at 330 kev in the same manner as the gamma-rays. Burcham and Devons[5] have shown that the excitation curve of the short range alpha-particles is the same as that of the gamma-rays over a range of proton energies from 300 to 950 kev.

Electron pairs were the next product of the disintegration of fluorine which were observed. Fowler and Lauritsen[17] in 1939 found a soft radiation, in addition to the characteristic x-radiation, coming from the fluorine target. When they bombarded a fluorine target with 820- or 1130-kev protons they showed by absorption experiments that the radiation was composed of electrons and not gamma-rays. They substantiated these observations by cloud-chamber measurements with a bombarding energy of 820 kev. These cloud-chamber experiments showed that the radiation consisted of electron pairs with a total energy of 5.9 ± 0.5 Mev. Streib, Fowler, and Lauritsen[6] have observed the excitation curve for this soft radiation and have found no pairs below 650 kev. They discovered resonances for the soft radiation at 850, 1140, 1220, and 1350 kev; only at 820 and 1130 kev have they shown that this soft radiation is composed of electron pairs. The proton energies of the pair-resonances do not coincide with the gamma-ray resonances. The reaction to which the pairs are attributed is the following:

$$\begin{array}{c} _9F^{19}+{_1H^1}\rightarrow{^*_{10}Ne^{20}}\rightarrow{^{\pi*}_8O^{16}}+{_2He^4}+Q_4, \\ ^{\pi*}_8O^{16}\rightarrow{_8O^{16}}+\pi+4.9\text{ Mev.} \end{array} \quad (4)$$

The emission of pairs in place of gamma-rays is attributed to the fact that the $^{\pi*}_8O^{16}$ has a total angular momentum equal to zero and so the emission of a single gamma-ray is forbidden.[18]

The experiments to be described below were undertaken with the purpose of determining the widths of the resonances in the excitation curves of the gamma-rays and the pairs. With improved resolution it was expected that a number of new resonances would be resolved, and that the natural widths of the already known resonances would be determined.

[15] W. E. Bennett, T. W. Bonner, E. Hudspeth, H. T. Richards, and B. E. Watt, Phys. Rev. **59**, 781 (1941).

[16] W. B. McLean, R. A. Becker, W. A. Fowler, and C. C. Lauritsen, Phys. Rev. **55**, 796 (1939).

[17] W. A. Fowler and C. C. Lauritsen, Phys. Rev. **56**, 835 (1940).

[18] J. R. Oppenheimer and J. S. Schwinger, Phys. Rev. **56**, 1066 (1939).

EXPERIMENTAL ARRANGEMENTS AND PROCEDURES

The proton accelerator was the Rice Institute pressure Van de Graaff generator which had been used previously.[15] In the present experiments the generator was modified by the addition of an energy selector and a potential stabilizer.

Energy Selector

An annular ring type of magnet, similar in design to that used by Rutherford, Wynn-Williams, Lewis, and Bowden,[19] deflected the protons through 90° and resolved the molecular and atomic beams. It was simultaneously used to define the energy of the beam striking the target by the addition of a narrow slit at the line where the beam was focused after being bent through 90°. The arrangement is shown in Fig. 1.

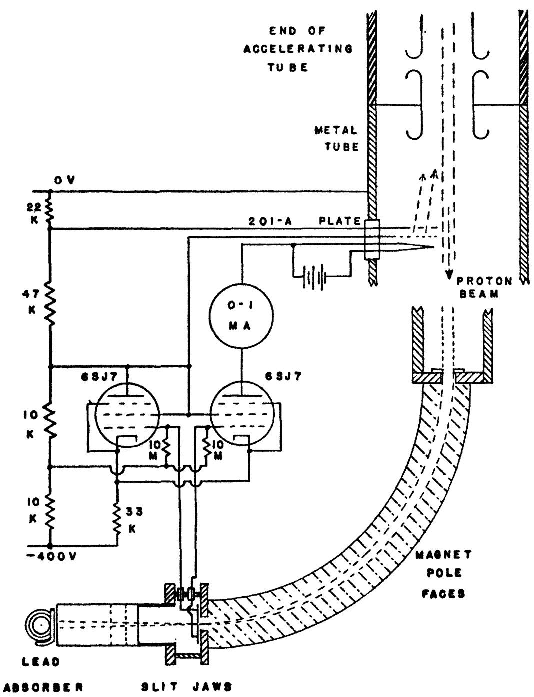

FIG. 1. Diagram of the experimental arrangement showing the magnetic energy selector and the electronic potential regulator. The proton-beam passes through the two insulated jaws of the narrow slit and proceeds to the target. The modulated electron current goes up the vacuum tube in the reverse direction to that of the positive ion-current. The 0–1 milliammeter measures the modulated electron current which leaves the electron gun; the current through this meter serves as an indicator of whether the stabilizer is centered within its limits of regulation.

[19] Lord Rutherford, C. E. Wynn-Williams, W. B. Lewis, and B. V. Bowden, Proc. Roy. Soc. **A139**, 617 (1933).

The radius of curvature of the beam of protons was 26 cm and the slit width was 0.015 cm. Observation of the focused beam of protons showed its width to be approximately 0.02 cm when the energy of the protons was 1 Mev. The expected width due to the finite size (1 cm) of the entrance aperature was 0.010 cm and the maximum energy spread possible because of voltages in the ion source was 1000 volts or 0.012 cm at the focal line. It is believed that the position spread due to aberrations in the focusing system was less than ±0.05 percent, under the condition of maximum current through the slit.

Potential Stabilizer

To reduce the energy spread in the emerging proton beam and to maintain a steady current through the narrow slit, a stabilizer for the potential of the proton accelerator was constructed by insulating the jaws of the narrow slit and constructing an electronic circuit to alter the accelerating potential so as to maintain equal currents to the two jaws. The diagram of the potential stabilizer is shown in Fig. 1. The electron-gun sends electrons back up the vacuum tube to the ion source. The potential stabilizer works by modulating the electron current from the gun. Since the charging current on the belt of the electrostatic generator remains constant, a change in the electron current will produce a change in the potential of the generator. The circuit is made such that an increase in the current to the inner jaw will decrease the electron current up the vacuum tube, thus increasing the voltage so that the proton beam will be centered in the narrow slit. The time delay of this control system is extremely short since the electrons proceed up the vacuum tube at essentially the velocity of light. The total time delay around the circuit which includes the transit times of the protons down the vacuum tube, the electrons in the amplifier circuit, and the electrons up the vacuum tube is 2×10^{-6} sec. This time delay sets a lower limit to the theoretical potential stability which could be achieved with this circuit. An analysis of the circuit shows that the lower limit to the voltage fluctuations would be about 0.02 volt. However because the ion source had an internal accelerating voltage of 1000 volts, the protons would be expected to have a

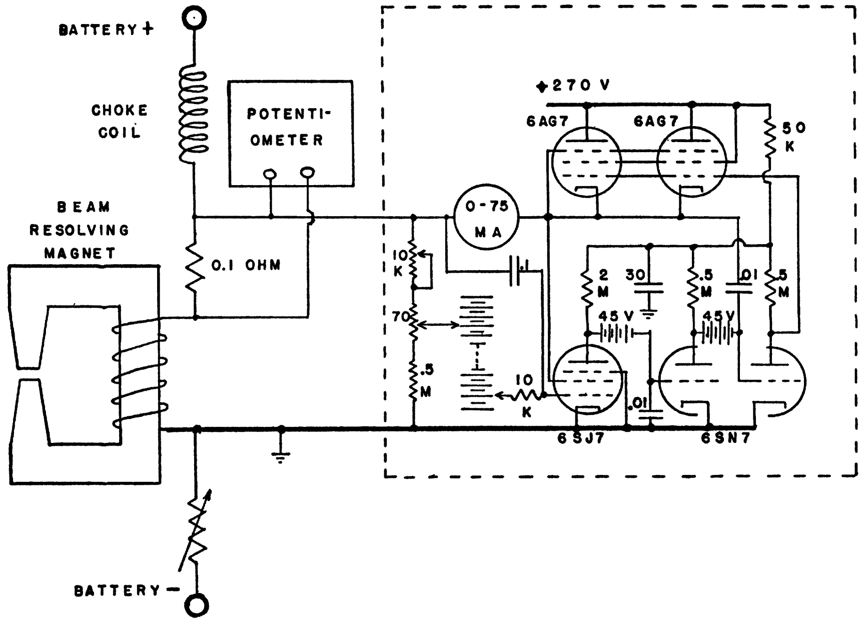

FIG. 2. Diagram of the electrical circuits which supply and measure the constant current to the magnetic analyzer.

spread in energy of several hundred volts and hence, it would not be useful to approach this theoretical limit with the present ion source. The calculated fluctuations in potential using the circuits of Fig. 1 are ±150 volts. This is somewhat smaller than the expected spread from the ion source and one-fourth the energy spread permitted by the narrow slit when operating at 1 Mev.

Current Regulator for Electromagnet

The current in the deflecting magnet was held constant by regulating the voltage which was applied to the coils. The diagram of the apparatus is shown in Fig. 2. The choke coil raises the impedance of the source for all the high frequency components of the supply voltage which was a 130-volt battery continuously charged by a generator. The potentiometer measured the total current through the coils by measuring the potential drop in the standard 0.1-ohm resistance and was capable of measuring the average current to 0.1 milliampere out of a total current of about 3 amperes. An oscillograph showed that the voltage across the coils of the magnet had no components in the frequency range 2 to 200,000 cycles per sec. of amplitude greater than 0.05 percent of the direct component, and the potentiometer showed no current fluctuations of lower frequency exceeding 0.01 percent. Owing to the large inductance of the magnet it is believed that the magnetic field was held constant to within 0.01 percent for the several minutes required to obtain one point on an excitation curve.

Because of the hysteresis in the iron, it took approximately 1.5 percent greater current to produce the same value of the magnetic field on increasing the field than when decreasing the field; so in running an excitation curve the convention of always increasing the current in the magnet was adopted. With this convention the displacements of excitation curves from day to day were less than 0.2 percent. Experience indicated that temperature variations in the air conditioned laboratory could explain most of the observed displacements.

Targets

The desired target thicknesses were in the range of from 500 to 2000 volts in stopping power. The thicker targets were used for survey experiments where it was expedient to take larger voltage intervals. All targets were prepared by evaporating a fluorine compound from a hot filament in a high vacuum onto a polished silver disk which was 3.2 cm in diameter. The compounds that were tried were CaF_2, MnF_2, and

ZnF_2. The ZnF_2 and MnF_2 were the most satisfactory because of their relatively low evaporation temperature. A micro-balance was used to weigh the deposit. The weights of the deposits ranged from 3 micrograms per square cm to 9 micrograms per square cm.

Detectors

Initially the detector for the gamma-rays was a bifilar electroscope in an iron cylinder 7 cm in diameter with walls 1 cm thick. It was filled with argon at 70 atmospheres pressure. Next, a Geiger counter shielded with 1.65 mm of lead was placed 0.7 cm from the target of fluorine. Comparison of the excitation curves in the region of the 862-kev resonance showed that the electroscope gave a larger background effect than did the Geiger counter, so it was decided to use the Geiger counter in the subsequent experiments.

To detect the softer radiation (electron pairs) a window was cut in the lead shield and the target holder made thin enough to admit electrons to the Geiger counter. The materials in the path of the electrons were 0.5 g/cm^2 of silver, 0.3 g/cm^2 of aluminum, 0.2 g/cm^2 of glass and 0.1 g/cm^2 of copper. The relative intensity of the soft radiation was determined by subtracting the yield observed with the lead absorber in place from the yield observed without the absorber. To compare the pair-yield with the gamma-ray yield corrections were made for the different probability of detection. Under the conditions of our experiments the gamma-rays were calculated to have approximately one-tenth the efficiency of counting as do pairs with a total kinetic energy of 4.9 Mev. In case some of the resonances are caused by pairs with a different energy or to soft radiation of another type, then the comparison factor between hard and soft radiation will be in error. The calculation of absolute yields of disintegrations has not been made, since Streib, Fowler, and Lauritsen[6] have determined the absolute values very accurately. With our experimental conditions the addition of the 0.165 cm of lead absorber increased the efficiency of counting 6-Mev gamma-rays by enough to compensate for the small absorption of the rays by this amount of lead. The sensitivity of the Geiger counter was checked frequently with a one milligram sample of radium at a standard position.

Procedure

After setting the current in the magnet to the desired value, the potential on the proton accelerator was adjusted to be within the range of the potential regulator. At each voltage, the time and total charge required to give several thousand counts in the Geiger detector were observed for the two conditions, lead absorber in position and out of position. The number of protons striking the target was determined by means of a current integrator described elsewhere.[20] The background count in the Geiger counter when the proton beam hit an iron shutter in place of the target was observed as a function of the x-ray intensity from the high voltage apparatus. Frequent readings of the x-ray intensity were made near the source of this radiation and these were used to compute the background. This was necessary since the x-ray intensity varied. In general this background was small in comparison to the effect due to gamma-rays at resonances, but was comparable to the gamma-ray effect in regions widely removed from resonances. A run with a blank silver target showed no increase over background within the experimental error. The voltage of each point on the excitation curve was obtained from a curve relating voltage as a function of magnet-current. The resonances at 927, 1335, and 1363 kev[14] were used to construct this curve.

RESULTS

The experimental results are shown in the graphs of Figs. 3–5. Five different targets were used to obtain these data. The precision in determining the yield of gamma-rays was considerably greater than that for pairs, since the yield of pairs is obtained by subtracting two measurements which sometimes were nearly equal. In order to improve the accuracy of the pair points, two or more neighboring points were averaged. Because of the necessity of this procedure and because of the reduced accuracy in determining pair points sharp pair resonances of weak intensity would have been missed.

[20] B. E. Watt, Rev. Sci. Inst. **17**, 334 (1946).

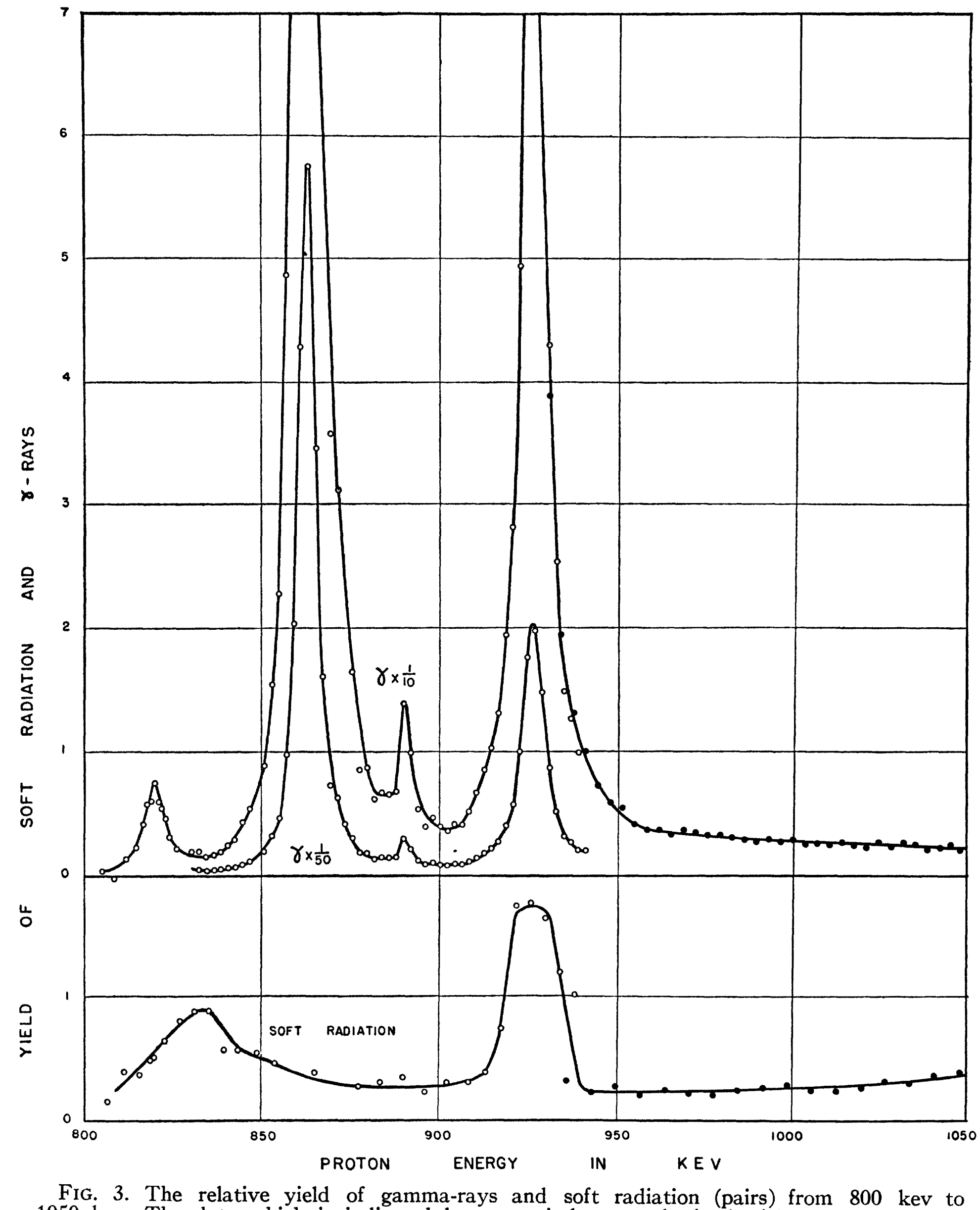

FIG. 3. The relative yield of gamma-rays and soft radiation (pairs) from 800 kev to 1050 kev. The data which is indicated by open circles was obtained with a 0.6-kev target of CaF_2, while that indicated by solid circles was obtained with a 1.8-kev target of ZnF_2.

The curves of Fig. 3 show sharp resonances for gamma-rays at 820 and 890 kev as well as the previously known resonances at 862 and 927 kev.[14] The curves for soft radiation (pairs) show broader resonances at 832 and 925 kev. The resonance at 832 kev is that discovered by Streib, Fowler, and Lauritsen[6] while the resonance at 925 kev was not observed by them. This resonance at 925 kev appeared relatively less intense when a thicker target of ZnF_2 was bombarded. Streib, Fowler, and Lauritsen also used thicker targets in their experiments. For this reason it appears likely that this resonance is not from F^{19} atoms but from some contaminant on the surface of the target, probably carbon or oxygen which are nearly always present in small quantities. Unfortunately no systematic study of the excitation curve of soft radiation from

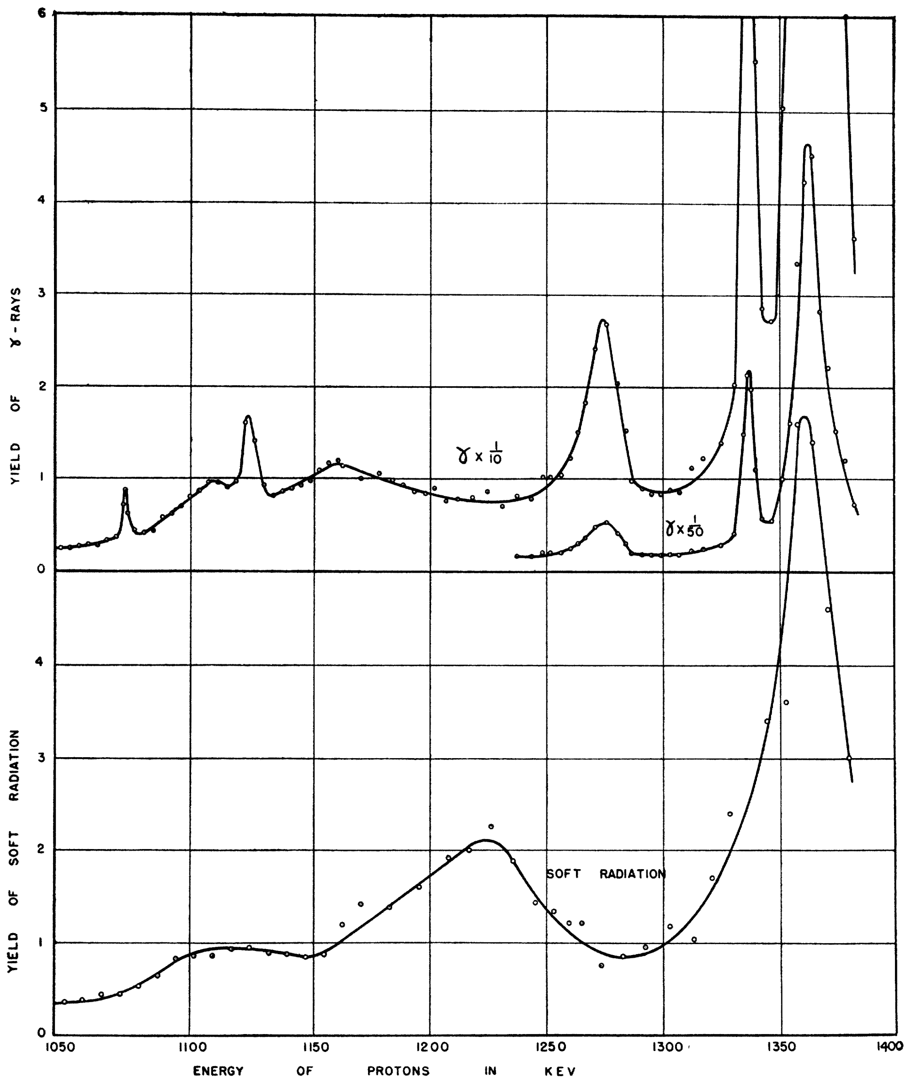

FIG. 4. The relative yield of gamma-radiation and soft radiation (pairs) from 1050 kev to 1400 kev. The data was taken with two different 1.8 kev targets of ZnF_2.

carbon or oxygen bombarded by protons has been obtained in the vicinity of 925 kev. This radiation may be a very low energy gamma-ray or more likely it is a beta-ray with an energy greater than 2 Mev. Radioactive ${}_9F^{17}$ has been formed at much higher energies by proton bombardment,[21] and it is quite possible that the effects observed are from radioactive ${}_9F^{17}$ which is made at a resonance in the capture reaction.

$$\begin{aligned} {}_8O^{16}+{}_1H^1 &\rightarrow {}_9F^{17}+\gamma+0.5 \text{ Mev.} \\ {}_9F^{17} &\rightarrow {}_8O^{17}+e^{+}+2.1 \text{ Mev.} \end{aligned} \tag{5}$$

[21] L. A. DuBridge, S. W. Barnes, and J. H. Buck, Phys. Rev. **51**, 995 (1937).

In Fig. 4 the excitation curves of the hard and soft components of the radiation are extended up to 1400 kev. The excitation curve of gamma-rays exhibits sharp resonances at 1076 and 1122 kev as well as the previously known resonances at 1274, 1335, and 1363 kev. Two broader gamma-ray resonances were found at 1107 and 1161 kev. The excitation curve of the soft radiation (pairs) shows resonances at 1100, 1220, and 1363 kev.

The widths of the resonances in Fig. 3 and Fig. 4 vary over wide limits. The half-widths of resonances greater than 5 kev were determined from the curves of Figs. 3 and 4 when drawn to

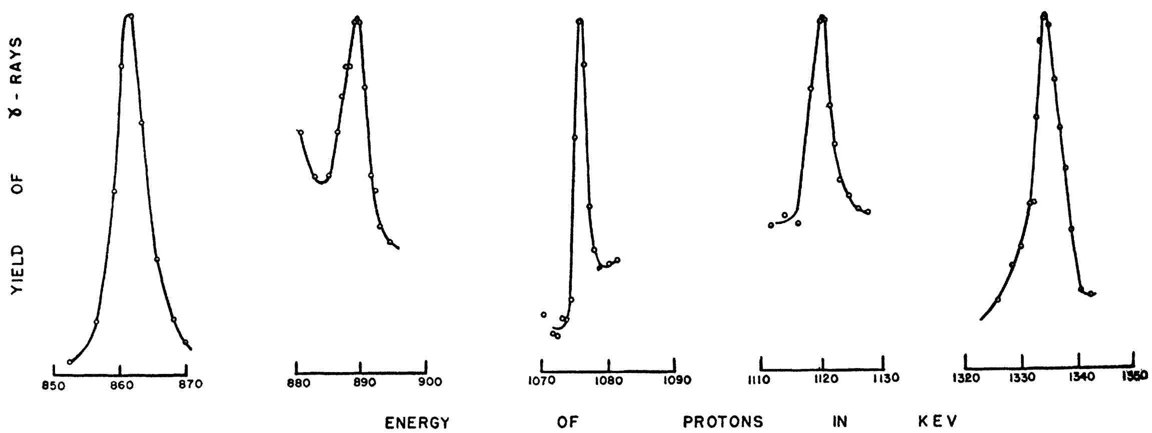

FIG. 5. Excitation curves to obtain the half-widths of the narrow resonances. The yields of the resonances have been normalized to the same value. The targets used were all 0.6 kev in equivalent thickness. CaF_2 was used to obtain the resonances at 862 and 890 kev; ZnF_2 was used in observing the resonances at 1076 and 1122 kev; and MnF_2 was used on the resonance at 1335 kev.

a large scale, and their values are given in Table I. In order to investigate the widths of the narrower resonances, excitation curves were carried out with targets whose equivalent thickness was only 0.6 kev. These excitation curves are shown in Fig. 5, and the half-widths are given in Table I. The narrowest experimental half-width is 1.9 kev for the resonance at 1076 kev. Since all the other half-widths are more than a factor of two larger than this, it can safely be said that they represent the natural widths of the resonance levels. The natural width of the level at 1076 kev must be less than 1.9 kev

TABLE I. Data concerning resonances in the emission of gamma-rays and pairs.

Type of resonance (γ-ray or pair)	Proton energy at resonance kev.	Half-width kev.	Relative peak intensity	Relative intensity* (peak × width)
γ	820	7.6	0.8	6.1
π	832	28.	0.08	2.2
γ	862	5.2	29.	150.
γ	890	4.8	1.0	4.8
γ	927	8.0	10.	80.
γ	1076	<1.9	0.5	1.0
π	1100	≈70.	0.06	≈ 4.
γ	1107	≈30.	0.8	≈24.
γ	1122	4.1	0.9	3.7
γ	1161	≈50.	0.8	≈40.
π	1220	85.	0.2	17.
γ	1274	19.	2.2	42.
γ	1335	4.8	9.0	43.
π	1362	36.	0.6	22.
γ	1363	15.	22.	330.

* The relative intensities of pair as compared to γ resonances may be in error by as much as a factor of two or more, because of the unknown angular distribution of the pairs and because of errors in the relative efficiencies of counting pairs and gamma-rays.

since the target alone had an average thickness of 0.6 kev and such a thin target may not have been uniform in thickness.

The widths of all the gamma-ray resonances are less than previously observed. However, the widths of the resonances in pair formation are somewhat larger than the rough estimates of Streib, Fowler, and Lauritsen.[6]

INTENSITIES AND WIDTHS OF THE RESONANCE LEVELS

The height of the potential barrier of F^{19} for protons is 2.3 Mev and the barrier of O^{16} for alpha-particles coming out of the compound nucleus is 4.3 Mev.[22] Since the barrier heights are considerably greater than the particle energies, the intensities and widths of the resonance levels should be strongly influenced by the penetrabilities through the barrier. This is especially true of particles with large angular momentum. The penetrability of *s*-protons (angular momentum = 0) varies from 0.042 to 0.36 as their energy is increased from 800 to 1400 kev, while the penetrability of *p* and *d* protons (angular momenta = 1 and 2 units) will be less.[22] Thus the probability of a proton entering the F^{19} nucleus and forming a Ne^{20} nucleus in a highly excited state (≈14 Mev) will increase by about a factor of 8 as the proton energy is increased from 800 to 1400 kev. Similarly the penetrability of *s*-alpha-particles varies from 0.09 to 0.31 as the

[22] H. A. Bethe, Rev. Mod. Phys. 9, 166 (1937).

energy of the alpha-particles is increased from 2.5 to 3.0 Mev. The probability of a disintegration resulting in a short range alpha-particle which leads to the emission of a gamma-ray or pair will be proportional to the penetrability of the proton times the competition ratio between the emission of the short range alpha-particle and the emission of a long range alpha-particle or the reemission of a proton.

The widths of the resonance levels are determined by the length of time which it takes the intermediate nucleus ($^*Ne^{20}$) to disintegrate. This time may be considered as composed of two parts, first the time necessary to concentrate the appropriate energy on the particle concerned, and second the length of time it takes this charged particle to leak through the barrier. The relation between the width of the level and the lifetime of the intermediate nucleus is given by the uncertainty relation: $\Delta E \Delta T \approx \hbar$. The lifetimes of the excited states of $^*Ne^{20}$ given in Table I vary from 0.8×10^{-20} sec. for the wide level at 1220 kev to 4×10^{-19} sec. for the very narrow level at 1076 kev. Except for the level at 1161 kev, the only two modes of disintegration of the levels which give gamma-rays are into O^{16} and a short range alpha-particle or into F^{19} and a proton (elastic nuclear scattering). The 1161-kev level probably also disintegrates with the emission of long range alpha-particles.

If all the disintegrations are produced by s-protons which resulted in the emission of s-alpha-particles, both the intensity and widths of the resonances might be expected to increase smoothly when the proton energy is increased from 800 to 1400 kev. Quantitatively the increase in intensity expected would be about a factor of 8. The increased ratio of widths of the levels would be less than a factor of 8, depending on the relative times involved in concentrating the energy on the disintegration particle in the compound nucleus and the time required for the particle to leak through the barrier.

The general trend of the data of Table I indicates an increasing intensity and width of levels as the proton energy increases. However there are wide variations in intensity and width from level to level. These variations can be explained qualitatively by assuming that the different resonances are produced by protons with differing angular momenta and that the short range alpha-particles may also have several different values of angular momentum. The widths of the levels would decrease as the angular momenta of the protons and alpha-particles increases since the barrier penetrabilities decrease with higher angular momenta. The most intense levels would then correspond to particles with low angular momentum while the weak levels would correspond to particles with higher angular momenta. A complete theoretical interpretation of the problem has been given by Schiff,[23] and we are indebted to him for discussions on the interpretation of our results. He finds that the widths and intensities of the levels can be explained satisfactorily if protons with angular momentum 0, 1, 2, 3, and 4 produce disintegrations and short range alpha-particles with angular momenta of 0, 1, 2, and 3 units result in the disintegration. He concludes that the gamma-rays come from one level in $^*O^{16}$ with even parity and angular momentum $J=1.$, and that the pairs come from a level in $^*O^{16}$ with even parity and zero angular momentum.

[23] L. I. Schiff, Phys. Rev. **70**, 891 (1946).