The Disintegration of Fluorine by Protons

by

J. F. Streib

Submitted in Partial Fulfillment

of the Requirements for

The Degree of Doctor of Philosophy

California Institute of Technology

1941

The writer is greatly indebted to Profs. C. C. Lauritsen and W. A. Fowler with whom the experiments described herein were performed for their assistance in the preparation of this report and for their helpfulness during his entire course of graduate study at the Institute.

Thanks are due to Prof. J. R. Oppenheimer for his discussions of the theoretical aspects of the investigation.

Abstract

The excitation functions for the production of long-range alpha particles, gamma rays, and electron pairs by the bombardment of F^{19} with protons were measured to 1.5 mev bombarding energy. To permit the identification of coinciding resonances in different types of radiation, the three types were observed simultaneously. The excitation functions are plotted. Approximate coincidence in two instances of pair and alpha resonances suggests that the same state of Ne^{20} may decay in such a way as to give rise to both types of radiation; the slight separation of the nearly coincident peaks might be explained as a displacement of the alpha peak from the true energy value due to an interference between the resonant process and the continuous rise upon which it is superimposed. If this conclusion is accepted, it follows that the state of O^{16} which gives rise to electron pairs has even parity, and it is possible to describe the production of pairs without assuming other than electromagnetic forces between the nuclear particles and the pair field. There is no coincidence of gamma-ray resonances with those of the pairs or long-range alpha particles.

The yields of the three modes of disintegration were estimated. At 0.334 mev resonance the intensity of gamma rays agrees within 20 per cent with a direct measurement of short-range alpha-particle production by Van Allen and Smith, giving additional evidence in favor of the accepted disintegration scheme.

A scheme of energy levels accounts for the existence of the various resonances, but not for their relative intensities. It is especially difficult to explain the high intensity of the gamma rays compared with the pairs and alpha particles.

I. Introduction

The reactions accompanying the bombardment of fluorine with protons have received considerable attention. The fact that--to within 1 per cent--natural fluorine consists of only one isotope, and the abundant yields obtained offer attractive simplifications for the experimentalist.

A. The Long-Range Alpha Particles

The Discovery of the Disintegration

In the report on their early work on disintegration by artificially accelerated particles Cockroft and Walton[1] announced the production of alpha particles in the bombardment of fluorine with protons. Similar observations were made by Oliphant and Rutherford[2]. The range of the alpha particles was less than that observed by later investigators and it is possible that they were spurious, being due to some contaminant[3]. The first observation of alpha particles which has been consistently verified was by Henderson, Livingston and Lawrence[3].

The Energy of the Alpha Particles

These observers reported a single alpha-particle group of range 6.7 cm; this was obtained with protons of 1.2 mev energy. Burcham and Smith[4] have since made a more careful determination of the range; with a proton energy of 0.85 mev, the alpha-particle range in a direction perpendicular to the beam was 5.90 cm, which corresponds to an energy release of 7.95 mev; again only a single group was found.

The Excitation Function of the Alpha Particles

In their experiment Henderson et al found a rapid increase in the yield as the proton energy was increased from 0.7 to 1.5 mev. Burcham and Devons[5] made a more precise investigation of the excitation for proton energies from 0.53 to 0.93 mev; in addition to a continuous increase in yield with increasing bombarding energy, they found two resonances at 0.72 and 0.83 mev. Their results are shown graphically in Figure 1.

The Origin of the Alpha Particles

The simplest explanation of the origin of these alpha particles is the reaction

$$F^{19} + H^{1} \longrightarrow {}^{\alpha}Ne^{20} \longrightarrow O^{16} + He^{4} \qquad (1)$$

which was proposed by Cockroft and Walton. Here the superscript α designates a particular kind of excited state in the intermediate neon nucleus. From the accepted values of the masses[6]

$$O^{16} = 16.0000 \pm 0.0000$$
$$H^{1} = 1.0081 \pm 0.0000$$
$$He^{4} = 4.0039 \pm 0.0001$$

and from the data of Burcham and Smith one calculates the mass

$$F^{19} = 19.0043 \pm 0.0001$$

which is in agreement with the value obtained from mass spectroscopy by Aston, who gave

$$F^{19} = 19.0045 \pm 0.0002$$

No evidence has been advanced against this explanation of the origin of the

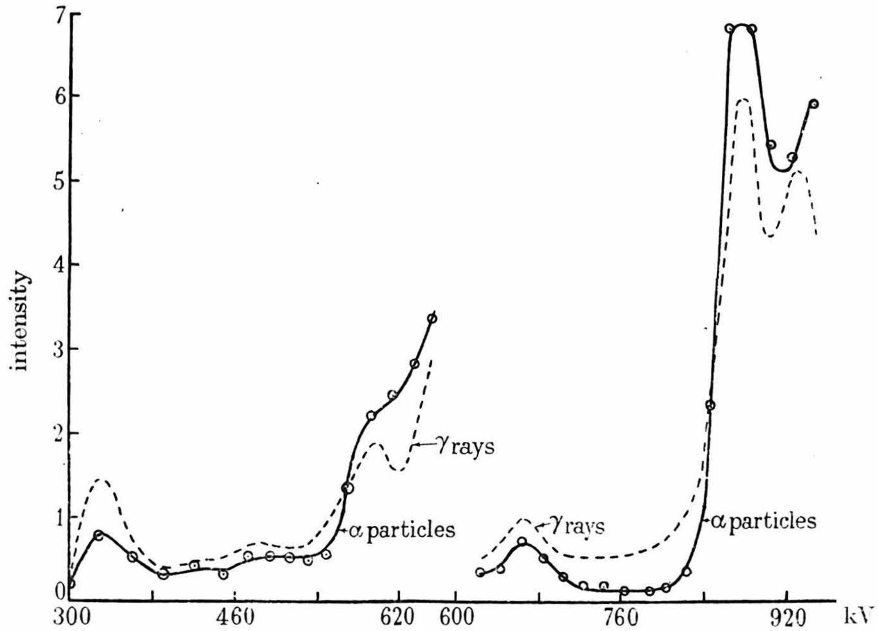


Fig. 1. The Excitation Function of the Long Range Alpha Particles. Measured by Burcham and Devons[5]

alpha particles, and it is now generally accepted.

B. The Gamma Radiation and the Short-Range Alpha Particles

The Gamma-Ray Spectrum

McMillan[7,8] first observed gamma radiation produced in the bombardment of fluorine with protons. The earliest estimates of the energy of this radiation were based on measurements of its absorption in lead. They were made by McMillan and by Crane, Delsasso, Fowler and Lauritsen[9], who employed ionization chambers and electroscopes to measure the intensity. The value of the absorption coefficient in lead, 0.49 cm^{-1} gave, according to the Klein-Nishina theory of the Compton effect, a quantum energy of 2 mev. However, the origin of such a gamma ray could not be accounted for. Oppenheimer suggested that the inferred value of the energy was too low, and that the absorption was due not only to the Compton effect, but also to pair production. Measurements of the absorption in other elements, tin, copper, and aluminum, showed that this suggestion was correct; the results obtained were all consistent with, and uniquely determined the value of approximately 5.4 mev for the quantum energy.

The technique of these measurements is open to serious criticism[10]. The radiation removed from the beam by the absorber is partly replaced by a secondary radiation whose presence makes the interpretation of the measurements difficult. This objection is eliminated in a method introduced and employed by Delsasso, Fowler and Lauritsen[11]. The gamma radiation ejects pairs from a thin-lead radiator in a cloud chamber; on alternate expansions the beam is passed through the absorbing body; the energy of each pair can be determined from the curvature in a magnetic field of the paths of the two members with sufficient accuracy to decide whether or not it was produced by the primary gamma ray. The transmission of the absorber is the ratio of the number of full energy pairs produced with the absorber in the beam to the number produced with the absorber removed. In this way the value 0.4 ± 0.1 cm^{-1} was obtained for the absorption coefficient in lead. This was not an accurate determination, but it served to check the other less reliable value. Using this same method Halpern and Crane[12] have found for the absorption coefficient in aluminum 0.062 ± 0.009 cm^{-1}. This is also in agreement with other data on the energy of the gamma ray.

The energy was also determined by Crane, Delsasso, Fowler and Lauritsen from the spectrum of positive and negative electrons ejected by the gamma radiation from a thick-lead sheet in a cloud chamber; the electron energies were again deduced from the path curvature due to a magnetic field. The value obtained for the quantum energy was 5.4 mev.

This method was later modified[11], and a thin-lead radiation was used. This made it possible to associate the two members of a pair and to determine their energies without having the uncertainty of an appreciable energy loss in the material. These observed spectra are shown graphically in Figure 2. The value obtained for the quantum energy was 6.0 ± 0.2 mev. The distinct structure of the curve leads one to believe that this is one of the most satisfactory direct determinations of the gamma-ray energy.

By measuring with coincidence counters the absorption in aluminum of the secondary electrons ejected by the gamma rays, Curran, Dee and Petržílka[13] arrived at values of 6.3 and 5.5 mev for the quantum energy, according as they based their conclusions on the maximum range in the absorber or the half-value thickness. Work of Dee, Curran and Strothers[14] with a magnetic spectrograph gave 6.5 mev.

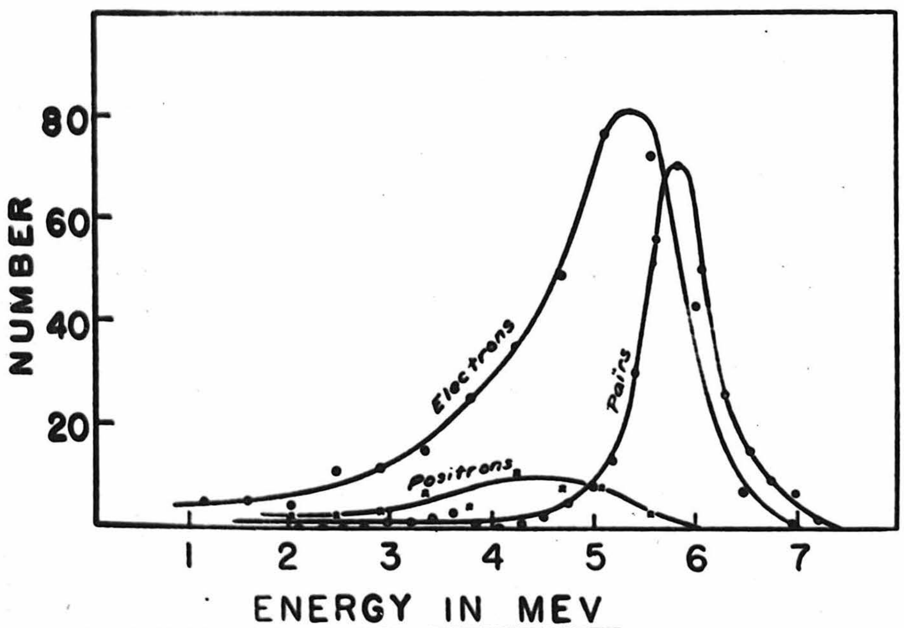


Fig. 2. The Gamma Ray Spectrum as indicated by secondary electron pairs ejected from lead. Measured by Delsasso, Fowler, and Lauritsen.[11]

In the preceding discussion the assumption has been implied that the gamma radiation is monochromatic. All of the investigators previously mentioned arrived at this conclusion. The absorption measurements of McMillan indicated a constant absorption coefficient over a wide range of absorber thicknesses. However, in view of the difficulties previously mentioned, this is no longer recognized as reliable evidence. The secondary electron spectra reveal only a single line. The most convincing evidence of this kind is the energy distribution of pairs mentioned above and shown in Figure 2. From this curve it is reasonable to conclude that there are present no other gamma-ray lines above 1 mev of intensity as high as 10 per cent of that of the principal one, and separated from it by as much as 0.8 mev, which is the experimental width of the peak.

In these cloud-chamber experiments there was a possibility that secondary electrons ejected from the walls of the chamber, and colliding with the radiator, would be interpreted as secondary electrons originating in the radiator. To eliminate as much as possible this uncertainty the method was modified by Gaerttner and Crane[15] who extended the target tube of the bombarding apparatus into the cloud chamber, and surrounded it with a cylindrical radiator. The wall of the target tube was made very thin, to prevent absorption of any soft radiation, and the radiator was made thin to obtain high resolving power. Both the distribution of electrons and of pairs, which they obtained, indicated the presence of the previously observed gamma-ray line, and in addition, a second line of about equal intensity at 4.0 mev. Later investigations[16] showed that the electrons making up this second line originate in the target itself, and it was decided that this line results from an unexpectedly high pair internal conversion of the gamma ray. More recent evidence, to be described below, suggests another possible explanation--that the formation of the pairs is a nuclear process.

Lauritsen, Fowler and Lauritsen[17,18], using a thick CaF_2 target, have found a 10.5 mev gamma-ray line having an intensity about 4 per cent as great as the principal line. It is present at 1 mev bombarding energy, but not at 0.33 mev. There is no experimental evidence to show that this radiation is not the result of proton bombardment of the calcium. The masses of the calcium isotopes are not accurately known, so calculations based on energy conservation cannot be made to demonstrate the possibility or impossibility of such an origin. One confidently expects a nucleus of the alpha-particle type, such as that of the principal calcium isotope, Ca^{40}, to have such a high binding energy relative to neighboring nuclei that this explanation of the origin of the gamma rays is precluded. The second most abundant isotope of calcium, Ca^{44}, is 2 per cent of the total, and it is conceivable that the following reaction describes the origin of the radiation:

$$Ca^{44} + H^{1} \rightarrow Sc^{45} + \gamma$$

Sc^{45} is the principal isotope of scandium. This proposal implies a yield from this reaction which, at 1 mev proton energy, is approximately four times that of the fluorine reaction which gives rise to the 6.2 mev radiation. However, experience and theory both show that such a high yield is not to be expected from a capture reaction. There are also the possibilities that the radiation is due to an unknown isotope of fluorine or to some contaminant. Further experiments to establish the source of this radiation should not be difficult.

The Resonant Nature of the Gamma-Ray Excitation Function

Long before the origin of the gamma radiation was understood its pronounced resonant character had been demonstrated by various investigators[13, 19,20,21]. The most extensive work was by Bernet, Herb and Parkinson[22]. A graph of their results is shown in Figure 3. This work showed that most of the resonance levels are very narrow; in fact the observed widths of most of the peaks are thought to be experimental. The low-energy part of the curve was investigated more closely by Burcham and Devons[5]. They were able to reduce the observed widths of the peaks at 0.33 and 0.67 mev to 6. kev, and presumably this is still chiefly experimental. However, the level at 0.59 mev was found to have a width of 35 kev.

The Origin of the Gamma Radiation. The Short-Range Alpha Particles

The simplest reaction to propose for the origin of the principal gamma radiation is:

$$F^{19} + H^{1} \longrightarrow (Ne^{20}) \longrightarrow Ne^{20} + \gamma \qquad (2)$$

Using the accepted values of the masses[6]

$$F^{19} = 19.0045 \pm 0.0002$$
$$H^{1} = 1.0081 \pm 0.0000$$
$$Ne^{20} = 19.9988 \pm 0.0001$$

one calculates for the quantum energy to be expected 13.1 $\pm$ 0.3 mev for an 0.33 mev proton. The discrepancy between this and the observed value definitely rules out this simple process.

But the fact that the calculated value is roughly twice the observed energy of the radiation suggests a cascade process in which two quanta of

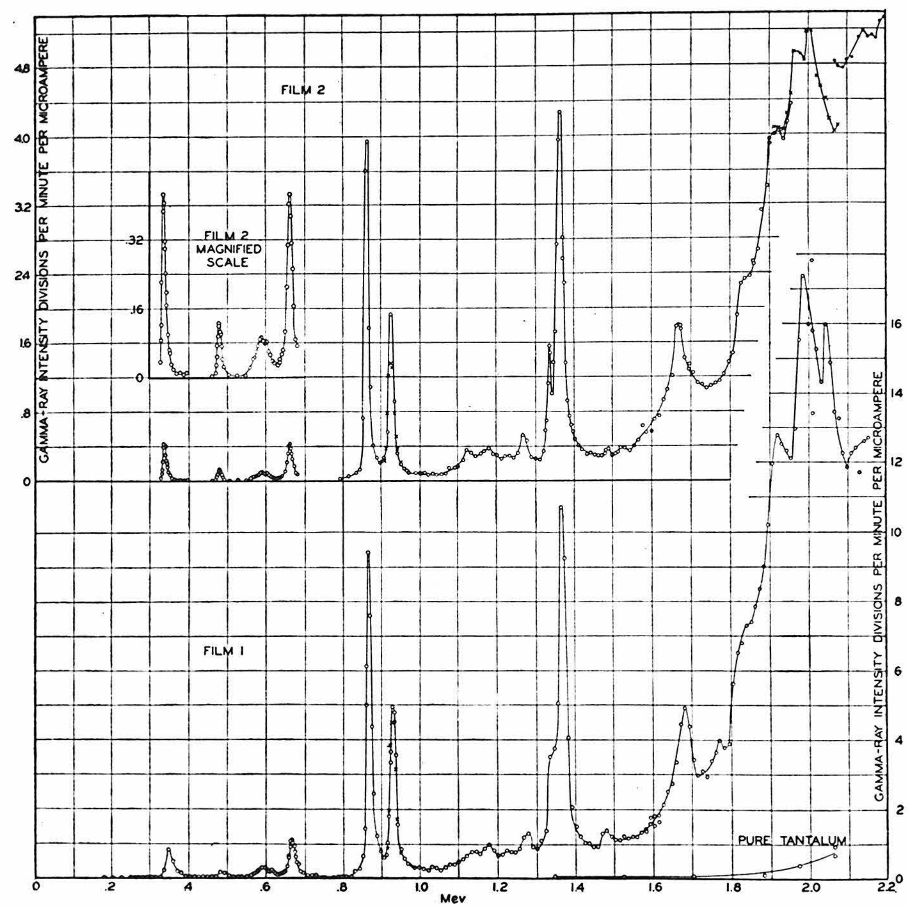


Fig. 3. The Excitation Function of the Gamma Radiation. Measured by Bernet, Herb and Parkinson.[22]

approximately equal energies are emitted:

$$F^{19} + H^{1} \longrightarrow (Ne^{20}) \longrightarrow {}^{*}Ne^{20} + \gamma_1$$
$$ {}^{*}Ne^{20} \longrightarrow Ne^{20} + \gamma_2 \qquad (3)$$

To detect the apparently simultaneous emission of two quanta which this proposal implies, Dee, Curran and Strothers[14] connected two gamma-ray counters in a coincidence circuit; coincidences occurred with a frequency less than 1 per cent of that which the proposed process would lead to.

This hypothesis was subjected to additional tests. According to Reaction (3) a change in proton energy would be accompanied by a modification of the gamma-ray spectrum; presumably the energy of the first quantum, γ_1, would increase by 19/20 of the increase in proton energy. However, when the bombarding voltage was raised from 0.330 to 0.860 kv, the gamma-ray spectrum, as indicated by the maximum range of its secondary electrons in aluminum, measured with coincidence counters, was constant to within 0.05 mev. The same conclusion was reached when the gamma rays were measured with a magnetic spectrograph; the constancy being within 0.1 mev.

A similar result was obtained by Lauritsen, Fowler and Lauritsen[17,18] who examined the gamma-ray spectrum by means of secondary pairs from a thin-lead radiator in a cloud chamber. Thick targets were bombarded at 0.425 mv, the radiation being produced exclusively at the 0.334 mev resonance, and at 1.00 mv, when the contributions are chiefly from the strong resonances at 0.862 and 0.927 mev. The quantum energies observed were 6.2 ± 0.2 and 6.3 ± 0.1 mev, respectively. On another occasion moderately thin targets were used, and the values 6.1 ± 0.2 and 6.0 ± 0.2 mev, respectively, were obtained at bombarding voltages 1.0 mv, the 0.862 and 0.927 mev resonances being effective here, and 1.4 mv, when the predominant effect is due to the 1.363 mev resonance. In these experiments the margins of error are not large, but the results indicate a constancy of the quantum energy with sufficient precision to rule out the hypothesis being tested. It is believed that the slight discrepancy between the two experiments is to be attributed to personal differences in measuring the curvature of the tracks. The results show, moreover, that the same transition gives rise to the gamma radiation at the 0.334, 0.862, 0.927 and 1.363 mev resonances.

Another possibility which has been considered is the following:

$$F^{19} + H^{1} \longrightarrow (Ne^{20}) \longrightarrow {}^{*}Ne^{20} + \gamma$$
$$ {}^{*}Ne^{20} \longrightarrow O^{16} + He^{4} \qquad (4)$$

But the objections given in the two preceding paragraphs will also apply here, and we must discard this proposal.

The ejection of a deuteron to form F^{18} is found, from the masses involved, to be energetically impossible.

The ejection of a neutron to form Ne^{19} is not to be expected. This nucleus would lie below the stable isotope distribution, and would probably be positron-active, and so produce F^{19}. This over-all process would then consist simply of the conversion of the proton into a neutron and a positron, and this is energetically impossible at the bombarding energies used.

The now accepted explanation of the origin of the gamma rays is the following:

$$F^{19} + H^{1} \longrightarrow {}^{\gamma}Ne^{20} \longrightarrow {}^{\gamma}O^{16} + He^{4}$$
$${}^{\gamma}O^{16} \longrightarrow O^{16} + \gamma \qquad (5)$$

According to the masses and the gamma-ray energy these alpha particles would have about a 1 cm range. No such group of alpha particles had been observed in the earlier work on alpha-particle production. Owing to the presence of scattered protons this would have been impossible except at low bombarding energies. An unsuccessful search for this short-range group had been made by Burcham and Smith[4]. However, at the time of their work the energy of the gamma radiation was thought to be 5.7 mev, and using this figure they calculated for the range of the alpha particles, a value which is now known to be too large. Under the conditions of their experiment--0.85 mv bombarding voltage--the range of these alpha particles is still less than that of the scattered protons.

When the higher values for the gamma-ray energy were obtained, the search for the short-range alpha particles was renewed. Calculations based on the new data indicated that only at proton energies less than 0.5 mev would the range of the alpha particles exceed that of the protons. These short-range alpha particles were first observed by McLean, Becker, Fowler and Lauritsen [23,24] who used a proton energy of 0.35 mev. These observers also showed that this production of alpha particles displayed a resonance between 0.30 and 0.35 mev. Such a resonance was already known to exist in the production of gamma radiation, and the association of the alpha and gamma rays seems quite certain. Similar results were obtained almost simultaneously by Burcham and Smith[25]. Burcham and Devons[5] extended this work by showing that the excitation function for the short-range alpha particles is identical with that of the gamma radiation in the proton energy range from 0.30 to 0.95 mev. This excitation function has a very striking structure which makes the comparison quite definite. In this work it was necessary to deflect the scattered proton beam by means of a strong magnetic field. Their resolution, particularly in the alpha-particle measurements, was not good, but there is an obvious correspondence between the prominences of their curve and the six known gamma-ray resonances which lie in this energy range. From the range of the alpha particles, 0.86 ± 0.05 cm, and the masses involved, McLean et al calculate the Q of Reaction (5) to be 1.74 ± 0.10 mev. This leads to the value 6.2 ± 0.2 mev for the gamma-ray energy. This is in agreement with the best direct determinations. This indirect measurement should give the most reliable value. Within the experimental error, the same value was obtained by Burcham and Devons. These investigators also showed that at the 0.33, 0.66 and 0.87 mev resonances the differences of the alpha-particle energies are* 3/4 of the corresponding differences in bombarding energy. This is the result predicted on the basis of Reaction (5). On the other hand, if we assume, as implied in Reaction (4), that the alpha particles always originate in the same transition, whatever the bombarding voltage, we would expect the energy (of those alpha particles emitted perpendicularly to the beam) to decrease by 1 per cent of the increase of proton energy.

These results, together with the previously mentioned observations on the gamma-ray spectrum, provide very conclusive evidence that Reaction (5) describes the production of the gamma radiation at the 0.334, 0.479, 0.589, 0.660, 0.862, 0.927 and 1.363 mev resonances. These resonances contribute approximately 75 per cent of the gamma radiation produced below 1.5 mev bombarding energy.

*The incorrect value 4/5 for this ratio was published. The experiment agrees more closely with the correct value 3/4.

Of course, there also is the possibility of a reaction similar to Reaction (5) in which the alpha particle is formed in an excited state, and subsequently emits a photon:

$$F^{19} + H^{1} \longrightarrow (Ne^{20}) \longrightarrow O^{16} + {}^{*}He^{4}$$

$$ {}^{*}He^{4} \longrightarrow He^{4} + \gamma \qquad (6)$$

However, no state of the helium nucleus so near to the ground state as is here required by the quantum energy has been suggested by the many reactions in which alpha particles are produced.

If the weak, 10.5 mev gamma-ray line is due to proton bombardment of F^{19}, consideration of the energies shows that it can originate only in the manner described by Reaction (3). Bonner's[26] measurement of the neutron spectrum of the reaction

$$F^{19} + H^{2} \longrightarrow {}^{*}Ne^{20} + n^{1}$$

demonstrates the existence of six excited states of the Ne^{20} nucleus (See Fig. 8). In this scheme of levels there are at least two transitions having the correct energy which could be postulated as the origin of this radiation. If the above explanation is correct, there must be associated with this high-energy radiation one or more gamma rays having a total energy of about 4 mev. Such radiation would be difficult to detect in the presence of the intense line at 6.2 mev. The low intensity of the 10.5 mev line relative to the principal line might be attributed to a competition between Reactions (3) and (5), but then it is difficult to understand the absence of the high-energy line at the lower bombarding voltages where Reaction (5) still occurs.

The experimental information is so meager that it is not profitable to enter into an extensive discussion.

Recent (unpublished) work of Becker, Fowler and Lauritsen indicates that in the region of bombarding energies from 1.1 to 1.3 mev there are no short-range alpha particles associated with the fairly intense gamma radiation--although there are short-range alpha particles associated with the production of pairs (See below.). It may be that this part of the excitation curve, where the quantum energy has never been measured, is due to the 10.5 mev gamma ray. This throws no additional light on the question of the origin of the radiation, except to eliminate the possibility that it is due to calcium, for the work of Bernet et al shows that the gamma radiation in this region is present when the target does not contain calcium.

C. The Electron Pairs

The Identification of the Pairs. Their Excitation Function

Using a thin walled target tube and a thin walled electroscope, Fowler and Lauritsen[27] searched for and found a soft radiation. Absorption measurements with aluminum and lead at bombarding energies 0.82 and 1.13 mev indicated that the radiation was electrons, not gamma rays, which conclusion was confirmed by cloud chamber observations, which showed the radiation to consist of electron pairs of energy 5.9 ± 0.5 mev. By means of two electroscopes the excitation functions of the two types of radiation were observed simultaneously. The results, reproduced in Figure 4 show that the pair formation displays a set of sharp resonances distinct from those of the gamma radiation. These are apparently the same pairs observed by Halpern and Crane who had made no attempt to correlate the pairs and the gamma rays.

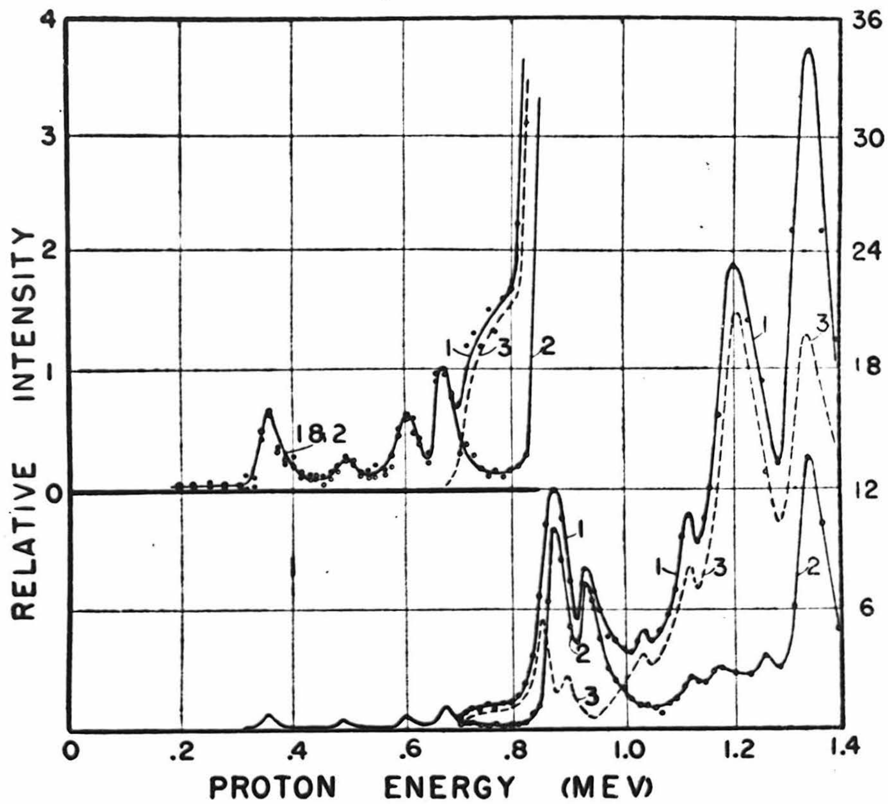


Fig. 4. The Electroscope Observations of Lauritsen and Fowler Indicating the Production of Beta Radiation. Curve 1--Radiation filtered by 0.5 mm of aluminum. Curve 2--Radiation filtered by 3.3 mm of lead in addition. Curve 3--The difference of Curves 1 and 2; this is presumably the excitation function of the beta radiation.

The Origin of the Pairs

The difference between the excitation functions of these two kinds of radiation indicates strongly that the pairs do not originate in the process of ordinary pair interval conversion, for theoretically the coefficient for this effect is less than 0.5 per cent, but in a nuclear process of a type not previously known. For example, at 1.22 mev proton energy, there is a peak in the pair excitation, but not in the gamma excitation. Moreover, at this point the intensity of the pairs is 10 per cent of the gamma-ray intensity. (This figure is based on the results of the present experiment, but the disagreement with theory was already appreciated.) The reaction proposed for the formation of the pairs is:

$$F^{19} + H^1 \longrightarrow {}^{\pi}Ne^{20} \longrightarrow {}^{\pi}O^{16} + He^4$$
$$ {}^{\pi}O^{16} \longrightarrow O^{16} + e^- + e^+ \qquad (7)$$

An apparently satisfactory explanation of this unusual process is that the state ${}^{\pi}O^{16}$ has the angular momentum $j = 0$; then decay to the ground state O^{16} which is known to have angular momentum $j = 0$ cannot take place with the emission of a single quantum. Calculations of Oppenheimer and Schwinger[28] show that pair formation under these conditions is more probable than the emission of two quanta. The questions involved in this calculation are mentioned below.

One must also consider the possibility that the pairs are formed by transition in the Ne^{20} nucleus. But the existence of many low-lying levels in this nucleus[26] makes it unreasonable to expect that gamma transitions from any state 5.9 mev above the ground state are rigorously forbidden (See Fig. 8).

Recently in this laboratory Becker, Fowler and Lauritsen have observed a group of short-range alpha particles associated with the prominent pair resonance at 1.22 mev. The alpha particles were magnetically separated from the scattered protons. Cloud-chamber measurements of the range of the alpha particles gave for the pair energy 5.9 mev in agreement with the previous work of Fowler and Lauritsen.

D. The Purpose of the Present Experiment

In accounting for the pair formation it was necessary to assume the state $^{\pi}O^{16}$ had angular momentum $j = 0$, but the parity is still undetermined. It would be interesting to know the parity of this state. For if the parity is odd, pair formation can take place only as a result of a non-electromagnetic coupling between the nuclear particles and the pair field such as is postulated in the Gamow-Teller theory of nuclear forces. On the other hand, if the parity is even, pair emission can occur as a result of ordinary electromagnetic forces. If it could be shown that transitions to the states $^{\pi}O^{16}$ and O^{16} from the same level in Ne^{20} occur, this would establish the parity of $^{\pi}O^{16}$ as even; a negative result would leave the parity undetermined[28]. The experiment to be described was undertaken by Professors Lauritsen and Fowler and the writer to see if such information could be obtained from the excitation curves in the region of higher voltages.

Estimates of the yields of the three types of radiation were made. Any satisfactory theory of the nucleus must, of course, account for the relative and absolute yields. Also, a knowledge of the gamma-radiation intensity should be useful in experiments on photo-disintegration.

II. The Experiment

The High-Voltage Apparatus

The source of high-velocity protons was the pressure Van der Graaff generator and accelerating tube built and used by Lauritsen, Lauritsen and Fowler, and previously described[17].

It was desired to increase the maximum operating voltage somewhat. After a certain point the maximum voltage did not increase as the tank pressure was raised. It was thought that the potential was limited by breakdown inside the tube. Examination of the focusing electrodes showed their surfaces at the ends to be pitted, thus confirming this view. To remedy this situation the cylindrical focusing electrodes were replaced by another set in which the size of the gaps was increased from 3/8 inch to 5/8 inch, and their number doubled. The maximum operating voltage was increased from 1.3 to at least 1.7 mev; the results of the tests of the operating voltage are shown in Figure 5. The original electrodes had a radius 2-1/4 inches, thickness 1/8 inch and length 5 inches; the dimensions of the new electrodes differ from these only in that the length is 2 inches. This alteration introduced no difficulties in focusing. From our experience the maximum operating voltage is 75 kv per section with 50 kv per section a safe limit.

To improve the stability a set of negative point-to-plane corona gaps, adjustable from outside the tank, which serve to distribute the potential along the ring system, was installed. The tube and the supporting columns were subdivided by conductors in the grooves of the porcelain elements. Each conductor was connected to a corresponding ring and between adjacent rings were connected the corona gaps. The necessity of electrical connections between all conductors and the gap system cannot be overemphasized.

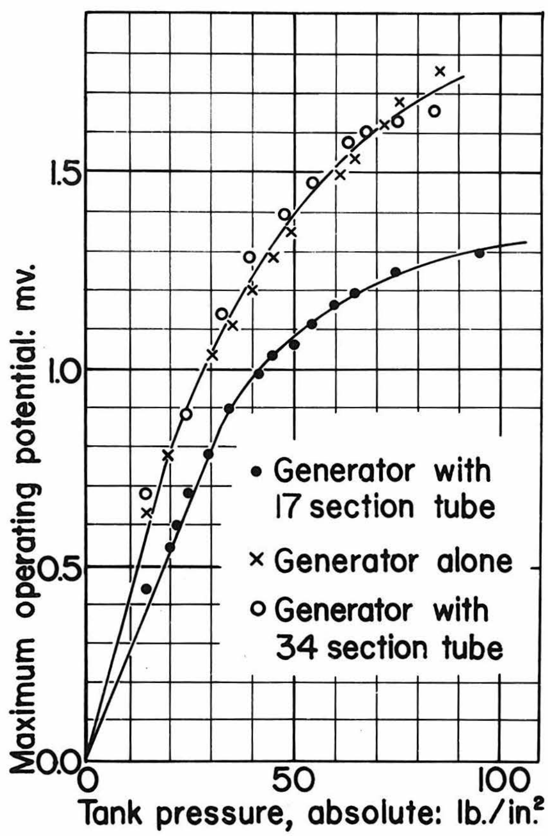


Fig. 5. The Maximum Operating Voltage vs. the Tank Pressure.

The corona current constitutes the principal drain of the charge on the dome, and the large steady current flowing in the gaps minimizes the effect of small erratic discharges, and in this way also helps to maintain a constant tube potential. The characteristics of the gap system are illustrated by the following data: When the tube is operating at 1 mv, it is most convenient to use a tank pressure of 60 pounds per square inch and a gap separation of 3/8 inch; under these conditions the current through the corona gap system is about 50 microamperes. To obtain a large corona current, the gap separation is kept as low as possible; of course, as the voltage is raised, the separation must be increased to prevent sparking. The corona current from a grounded needle, extending inward from a position on the wall of the tank just opposite the dome provides an additional current drain on the high potential end of the generator, to still further improve the voltage stability. The length of the needle extending inside the tank wall may be varied during operation; it is normally about 1 inch. The corona current from the needle is of the order of 40 microamperes.

The maximum voltage of the generator was limited by sparking along the charging belt. The situation was greatly improved by the installation of three sets of guides, equally spaced along the belt. Each set consisted of four 3/4 inch rods mounted in a horizontal plane, two, separated by 1/2 inch, serving to guide each side of the belt. They were connected to the nearest member of the ring system, and by their subdividing action tended to equalize the potential gradient along the belt and thus eliminate high local fields. This arrangement was suggested to us by Dr. E. U. Condon of the Westinghouse Research Laboratories who had successfully employed this method. However, the charging belt was the seat of still another trouble: Its flapping produced voltage fluctuations. The guides could not be effective in preventing this without pressing firmly against the belt, and this was objectionable due to the excessive friction and injury to the belt which it entailed. Therefore each set of guides was replaced by a single 4 inch roller, similar to the two upon which the belt runs, mounted between the two sides of the belt. They play the same role as the guides in distributing the potential along the belt, and in addition greatly improve the mechanical smoothness of the belt operation.

As a result of modifications which it has undergone, the ring system is at present in poor condition; the rings are not uniform in size nor true in shape, and the surfaces of some have been marred. It is believed that the replacement of the rings, especially those near the high potential end of the generator will increase the maximum operating potential. The size and shape of the porcelain elements of the supporting columns are such that an equal spacing of the rings is inconvenient. Moreover, with the present spacing, and with the focusing electrodes connected to the ring system, it is impossible to load equally the several sections of the tube. It is believed that when these conditions are rectified, an appreciable increase in maximum operating potential will be realized.

It is sometimes possible to observe in the focal spot of the ion beam a flickering which has the period of the charging belt; this appears to be due to voltage variations associated with the seam where the two ends of the belt are joined. Hence the voltage fluctuations should be reduced by the use of a seamless belt. There is also under consideration a method for automatic voltage regulation which involves the control of the corona current to the dome by means of a varying potential applied to the needle on the tank wall already mentioned.

Voltage Measurement

The tube voltage was measured with the generating voltmeter and checked during every run by some "landmark" on the gamma-ray excitation curve. The steadiness of the voltage was evident from the immobility of the magnetically analyzed ion beam. The homogeneity of the beam is shown by the fairly narrow and well resolved gamma-ray peaks (see below).

Current Measurement

Some unsteadiness in the ion current made necessary an integrating device to measure the total charge carried by the bombarding protons during a run. The target, at the bottom of a Faraday cage, was bombarded by the beam defined by an aperture slightly above the entrance of the cage, and the charge accumulated by the cage was led into a condenser having good insulation, whose potential could be read continuously on an electroscope connected across it. This apparatus was calibrated by observing the electroscope deflection produced by a measured current flowing into the condenser for a measured time. Measurements of the ion current were always made with the condenser negatively charged so that the secondary electrons formed at the ~~deflecting~~ defining aperture were repelled from the cage.

The Targets

It was found that a thin target of TaF_5 formed by the action of hydrofluoric acid on tantalum as described by Bernet et al[22], and then polished, gave more dependable results than the targets formerly used in this laboratory made by depositing a thin layer of CaF_2 on a copper backing. Two thin target curves were made. Before the second set of data was taken, the target was well polished; being thinner, it then gave a smaller yield, but permitted greater resolution. The thick target was a heavy deposit of CaF_2 on a copper backing.

A formula has been derived[22] for estimating the thickness of thin targets from a comparison of the thin-target and thick-target curves: Let I(E) be the intensity in arbitrary units of gamma radiation obtained from the thin target with some fixed bombarding current at the bombarding energy E; let J_γ be the increase in intensity, that is, the height of the "step", corresponding to some resonance, obtained from a thick target with the same bombarding current; and let ε and ε' be the stopping power at the resonance energy of the thin and thick targets, respectively, and n and n' the respective densities of reacting nuclei in the targets; then, the thickness of the thin target in terms of the energy of the bombarding particle at the resonance energy is

$$H = \frac{n'}{n} \frac{\varepsilon}{\varepsilon'} \frac{1}{J_\gamma} \int I(E)\, dE \qquad (8)$$

where the definite integral is extended over the energy region which contains the resonance, and is evaluated graphically by measuring the corresponding area under the thin-target curve. For these measurements it is very convenient to use the two resonances, 0.862 and 0.927 mev together, for these close peaks are very much higher than any background upon which they may be superimposed. In this way the thickness of the thin target was found to be 8 kev for 1 mev protons during the first observations and 2 kev after polishing. More details of the measurements appear below.

The Measurement of the Radiation

The possibility of uncertainties in the voltage made it necessary to observe all of the radiations simultaneously. Otherwise resonances in two different radiations occurring close together could not be definitely established as separate or together. The arrangement of the measuring apparatus is shown in Figure 6.

The gamma rays were recorded in a Lauritsen electroscope shielded by 1/8 inch of lead. The combined effect of the pairs and gamma rays was recorded in a similar unshielded electroscope. This is the arrangement previously employed by Fowler and Lauritsen. The two electroscopes were placed as close as possible to the target. Within convenience the material between the target and the unshielded electroscope was reduced to a minimum to avoid absorption of the pairs. To decrease the background due to undesired radiation, principally X-rays and gamma rays originating from ion bombardment of parts of the tube, the electroscopes were almost completely enclosed in a lead box with one inch walls.

The target was inclined 45° with respect to the beam, and long-range alpha particles ejected at right angles to the beam were brought out of the tube through a thin aluminum window, whose stopping power, measured with the alpha particles from polonium, was equivalent to 1.8 cm of air. They passed through 1 cm of air, entered the ionization chamber through a similar window, and were counted by means of a four-stage linear amplifier and thyratron recording circuit; the performance of this apparatus was frequently checked with a polonium alpha-particle source. A diaphragm to limit the alpha-particle beam was located between the two windows. This usually was a 1/8 inch circular hole 3/4 inch from the center of the target, but was sometimes changed to accomodate the large variations in intensity over the voltage range investigated. The ionization chamber was placed in a position convenient for counting the alpha particles produced by the low-energy protons; then when the voltage was raised above 1.1 mv scattered protons were able to enter the

Fig. 6. Arrangement of target tube, electroscope and ionization chamber. The vertical proton beam, shown by dotted lines, is defined by the 0.25-inch hole in the quartz ring R. In aligning the target tube, the position of the beam is observed through the transparent Plexiglas tubing M by the fluorescence produced in the quartz ring. The connection Q is to the current integrator. A negative potential on G prevents erroneous current measurements resulting from a gain or loss of secondary electrons. The lead box B completely encloses the electroscopes E and F except for holes admitting the microscope tubes, holes for illumination, and the beveled slot just large enough to accommodate the target tube P. S is the 0.125-inch lead shield which absorbs electrons originating in the target. Electroscope E records only gamma radiation. Electroscope F records both electrons and gamma radiation. The material between the target and this electroscope is: the target backing, T = 0.0010 inch of tantalum, the target holder = 0.008 inch of phosphor bronze, the target tube = 0.004 inch of German silver, and the electroscope wall = 0.030 inch of aluminum. The path of an alpha particle emitted perpendicularly to the proton beam is shown by a dotted line. The particle leaves the tube through the 0.00025-inch aluminum window W, and enters the ionization chamber C through the similar window V. The alpha-particle beam is limited by the aperture D. Because of the large window V, the position of the ionization chamber is not critical. The aluminum absorber A stops scattered protons.

chamber. It would have been possible to move the ionization chamber farther from the tube so as to count only the alpha particles, whose range is also increased, but to avoid disturbing the geometrical arrangement it was thought better to insert in front of the chamber aluminum foils to absorb the protons when using potentials over 1 mv; the number of absorbers was varied with the voltage. The correct stopping power of the absorber is not at all critical; it was varied in steps of 0.18 cm equivalent stopping power of air (0.13 mev for protons).

Experimental Procedure: The Excitation Functions

Observations were made at voltages differing by 12 kv from 0.3 to 1.6 mv. A single measurement required on the average about two minutes. The target was usually bombarded with 66 micro-coulombs, corresponding to 10 divisions of the current integrator. The length of the run was varied, depending on the intensities under observation. Below 0.6 mev the molecular ion beam was used.

At resonances the deflections of the radiation-recording electroscopes were of the order of 20 divisions. Background corrections, of the order of 0.5 divisions, depending on the length of the run, were applied to the electroscope readings. This correction was for the natural leakage, and did not include the effect of stray radiation excited in the tube. Between resonances the observed deflections were sometimes equal to the background correction. Judging from the reproducibility of the observations, the reliability of the electroscope data is about what one would expect from the fact that they can be read to about 0.1 division.

The counting rate of the alpha particles was sufficiently high that no background correction was needed, but not high enough to introduce important errors.

The Relative Sensitivities of the Electroscopes to Gamma Radiation

The pair excitation is determined by subtracting from the total reading of the unshielded electroscope the effect of the gamma rays as determined from the shielded electroscope. Thus it is necessary to know their relative sensitivities to gamma rays. The principal part of the ionization associated with the gamma radiation is produced by the electrons and the electron pairs ejected from the surrounding matter. However, an important part is produced indirectly through the effects of scattered radiation and the radiation accompanying the annihilation of the electron pair positrons. The magnitude of these secondary effects is greatly dependent upon the composition and geometrical arrangement of the material near the electroscope, especially when the material has a high atomic number, as in the present experiment. In view of the complicated nature of these effects and the difficulty of the calculations involved, it seemed best to make the comparison of the electroscopes without any change in the apparatus and using the gamma radiation in question. This was possible, for rough absorption measurements showed that with a bombarding voltage of 0.335 mv the intensity of pairs is at least very small. The presence of a few pairs would not modify the results appreciably. The sensitivity of the unshielded electroscope was found to be 2.0 times that of the shielded electroscope.

The Absolute Sensitivity of the Electroscope

To determine the yield of gamma rays a calibration of the absolute sensitivity of the electroscope was made by noting its rate of deflection while exposed to radiation of known intensity. To facilitate calculations in such a measurement it is desirable to surround the electroscope with a medium so dense that within a distance from the electroscope equal to the range of the secondary electrons, the intensity and composition of the radiation is uniform. One must be able to calculate the number of electrons ejected from this medium into the electroscope in terms of the radiation in question. Owing to the complications mentioned above, this is not practicable if the instrument is surrounded by lead. However, if a material of low atomic number is used, these complicating effects become inappreciable and may be disregarded. It should be pointed out that lead is not objectionable as a surrounding medium in the determination of an excitation curve, where only varying intensities of a fixed kind of radiation are involved, but is objectionable when a comparison is to be made between the absolute intensities of two gamma rays of different energies. The upper (shielded) electroscope, its shield removed, was placed in the center of a paraffin sphere 6 inches in diameter, and its deflection observed while it was exposed to the radiation from a 1.915 millicurie radium standard surrounded by 0.5 mm of brass and 1.0 mm of lead placed 100 cm from the electroscope.

Laurence[29] gives an empirical expression for the strength of a unit radium source filtered by a thickness of platinum T_{Pt}:

$$s = (8.98 - 1.17\ \text{mm}^{-1}\ T_{Pt})\ \frac{\text{roentgens cm}^2}{\text{hour millicurie}} \qquad (T_{Pt} > 0.3\ \text{mm})$$

The absorption of the harder components of the radium radiation (0.7 to 2.2 mev) in brass is about one-half that in lead[30]. The softer components are almost entirely removed by the filter. Thus, the filter is equivalent to 1.25 mm of lead. This was converted to an equivalent thickness of platinum from a knowledge of the densities, it being assumed that the mass absorption is approximately the same in lead (atomic number 82) and platinum (atomic number 78):

$$T_{Pt} = \frac{\rho_{Pb}}{\rho_{Pt}} T_{Pb} = \frac{11.3}{21.4} 1.25 = 0.66 \text{ mm}$$

whence

$$s = 8.98 - (1.17 \times 0.66) = 8.21 \frac{\text{roentgens cm}^2}{\text{hour millicurie}}$$

Since the second term of the expression is only 9 per cent of the first, no important error has been introduced by the approximations made in calculating the effect of the filter. If Q is the actual strength of the radium source, its effective strength is

$$S = sQ = 8.21 \times 1.915 = 15.7 \frac{\text{roentgens cm}^2}{\text{hour}}$$

With the softer components of the radiation removed, photoelectric absorption in the paraffin is unimportant. In view of the low atomic numbers of the constituents of paraffin, pair formation absorption may also be neglected. Data given by Lauritsen[31] shows that the true absorption (of energy) by the Compton effect is roughly the same for all components of the radiation. The value

$$_e\sigma_a = 0.9 \times 10^{-25} \text{ cm}^2$$

for the electronic cross section is a reasonable average value. The electron density in paraffin is

$$n = 3.1 \times 10^{23} \text{ cm}^{-3}$$

and the absorption coefficient and the attenuation factor are respectively

$$\mu = n_e\sigma_a = 3.1 \times 10^{23} \times 0.9 \times 10^{-25} = 0.0281\ \text{cm}^{-1}$$

$$A = e^{-\mu x} = e^{-0.0281 \times 5.0} = 0.87$$

where

$$x = 5.0\ \text{cm}$$

is the thickness of paraffin effective in absorbing the radiation. The factor A is so close to unity that the approximate treatment is justified.

One must also know the effectiveness, relative to air, of the surrounding medium in supplying secondary electrons to the electroscope. Calculations of Laurence[29] make this ratio readily available for those cases in which the Compton effect is the only important mechanism in the absorption of the radiation by the medium and atomic collission the only mode of energy loss by the secondary electrons. With gamma-ray energies between 1. and 2. mev, the values of the ratio for paraffin and for aluminum are constant to within 1 per cent and are respectively

$$B_{pa} = 0.93 \qquad B_{Al} = 1.06$$

The walls of the electroscope chamber are of aluminum and have a thickness 0.038 cm, which is about 1/5 of the range of the fastest electrons scattered by the radium radiation. Some average between these two values must be taken. An exact calculation would be difficult. Since a large fraction of the gamma rays have energies much less than the most energetic, and since the scattered electrons do not in general receive their maximum possible energy, it would seem reasonable to weight the two values equally: then we have for the ratio

$$B = 1.00$$

That is, this combination of paraffin and aluminum is roughly equivalent to the ideal air chamber. Since B_{pa} and B_{Al} differ by only 13 per cent, B cannot be in error by more than about 4 per cent. The presence of the aluminum wall could not be avoided, and it would have been better to have employed an aluminum medium, and thus avoid the uncertainty accompanying the combination of two materials.

We may now combine the various factors into an expression for the sensitivity in ion pairs per division of the electroscope. If the distance between the source and the electrope is r, the volume of the electroscope V, and e the electronic charge in electrostatic units, and a deflection of d divisions is produced during a time t, the sensitivity is

$$C = \frac{SBAV}{er^2 \cdot d/t}$$

In the present experiment

$$r = 100.\ \text{cm} \qquad V = 145.\ \text{cm}^3$$

$$d/t = 0.062\ \text{div sec}^{-1} = 223.\ \text{div hr}^{-1}$$

and

$$C = 1.85 \times 10^6\ \text{ions div}^{-1}$$

The Yield of the Gamma Rays

The electroscope, again unshielded, was placed inside the paraffin sphere and exposed to the radiation from a thick CaF_2 target, located just outside the sphere and bombarded with 1.04 mev protons. This voltage was chosen because here there is a low flat minimum on the excitation curve. From the electroscope deflection, the reading of the current integrator, and the geometry involved, the yield of gamma radiation in terms of roentgens was found. Consideration of the origin of the radiation justifies the assumption of its isotropic distribution. If we temporarily neglect the attenuation of the radiation in its passage through the paraffin surrounding the ionization chamber, we may write for the number of quanta leaving the target

$$\frac{4\pi w C r^2 d}{V m c^2 L B}$$

here V and C denote the same quantities as before; r, d and B have the same meaning as above, except that they now refer to the observations on the radiation in question; mc^2L is the kinetic energy of the secondary electrons produced per electron in air by a unit beam of radiation, that is, a beam of one quantum per unit area; w is the average energy loss of a secondary electron per ion pair formed in air.

Laurence's calculations give the following expression for mc^2LB:

$$mc^2LB = \int_0^{h\nu} \phi(h\nu,\ E_o) \int_0^{E_o} \frac{F_a(E)}{F_w(E)}\, dE\, dE_o$$

where $\phi(h\nu,\ E_o)$ is the distribution in energy E_o of the secondary electrons produced by the radiation, and $F_a(E)$ and $F_w(E)$ are the stopping powers for electrons of energy E in the air and in the wall material respectively. Laurence's succeeding formulas are not accurate for radiation having a quantum energy greater than 2 mev. In modifying Laurence's computations for application to the present problem it is necessary to take into account pair formation as an additional mechanism in the absorption of the radiation; a new term must be added to ϕ to represent the energy distribution of the positive and negative electrons. Also, radiative collisions contribute appreciably to the stopping of the secondary electrons and a corresponding term must be added to F_w, since this effect decreases the range of the electrons, and hence their effectiveness in producing ionization; the radiation term is not included in F_a, however, for this mode of stopping the electrons does not affect the ionizing ability of the electron as it traverses the air chamber. Since the more important of these two effects, pair formation, alters the result by only 10 per cent, only an approximate treatment is necessary. For a quantum energy of 6.2 mev, the values of mc^2LB obtained for aluminum and paraffin were respectively

$$mc^2(LB)_{Al} = 7.73 \times 10^{-25}$$

$$mc^2(LB)_p = 5.62 \times 10^{-25}$$

Again a weighted average between these values must be taken; in this case the relative weights were taken 1 to 3, respectively, giving

$$mc^2LB = 5.90 \times 10^{-25}$$

The weighting factors were obtained from a very rough consideration of the ranges and distribution of the secondary electrons; however, since the two quantities involved in the average are fairly close together, no important error has been introduced.

At this quantum energy an appreciable part of the energy of the secondary electrons is converted back into radiation. Since the intensity of this radiation is small compared with that of the primary beam, approximations may be employed in calculating its effect. A theorem given by Grey which has approximate validity when applied to the secondary radiation states that the energy absorption in the air and in the wall material are proportional to the stopping powers for electrons of these substances. A simple geometrical argument shows that directional effects are self compensating. An additional simplification results from the fact that the coefficient for the absorption of energy from a beam of radiation does not depend critically upon the quantum energy. It follows that the secondary radiation may be considered equivalent to an amount of primary radiation having the same total energy and emitted in the forward direction. Thus, at the same time, one can take into account both the effect of the secondary radiation and the small attenuation of the beam due to its passage through the material surrounding the ionization chamber by multiplying by the attenuation factor

$$A = e^{-\mu x}$$

Here the symbols have the same significance as before, except that they now apply to the radiation in question. In calculating μ the effects mentioned in the preceding paragraph must be included. The numerical values are[31]

$${}_e\sigma_a = 0.5 \times 10^{-25} \text{ cm}^2$$

$$\mu = n\,{}_e\sigma_a = 3.1 \times 10^{23} \times 0.5 \times 10^{-25} = 0.015 \text{ cm}^{-1}$$

$$A = e^{-\mu x} = e^{-0.015 \times 5.0} = 0.92$$

The calculations extending Laurence's work were carried out by Professor Fowler and have been described in more detail[32].

We may now write the complete expression for the number of quanta leaving the target during an observation:

$$n_\gamma = \frac{4\pi wCr^2 d}{AVmc^2 LB}$$

This was a measurement of the production of gamma rays from all the resonances below 1.04 mev. Equation (8) may be modified as follows: If Y_γ is the (integrated) yield of a resonance in arbitrary units, and h is the thickness (in terms of length) of the thin target

$$Y_\gamma = \frac{J_\gamma \varepsilon'}{n'} \text{ and } H = \varepsilon h$$

whence

$$Y_\gamma = \frac{1}{nh}\int I(E)dE \qquad (9)$$

Since n and h are independent of E, the yields of the several resonances are simply proportional to the corresponding areas under the thin-target curve.

The Yield of Pairs

There is more uncertainty in the determination of the yield of pairs. The absolute sensitivity of the lower (unshielded) electroscope was determined by the procedure described above. The cloud-chamber work of Fowler and Lauritsen had given an energy distribution of the numbers of the pairs roughly constant up to the maximum kinetic energy E_M = 4.9 mev. Now, if all the electrons lose the same amount of energy E_L, or are stopped, if their initial energy is less than that amount, in passing through the material between the target and the ionization chamber, the distribution in energy of the electrons in the chamber will also be constant up to a maximum energy $E'_M = E_M - E_L$. From this it follows that the number of pairs produced is

$$n_\pi = \frac{2\pi W C r^2 E_M R'_M}{E'^2_M} d$$

where W is the average energy lost per ion formed, here taken as 34 ev; C is the sensitivity in ions per division of the electroscope, r is an average of the distance from a point on the target to a point in the ionization chamber, here taken as the distance between centers of the target and chamber. R_M is the range in air of an electron of energy E_M; and d is the electroscope deflection associated with the pairs. So far we have ignored the effect of bremsstrahlung and annihilation radiation. This cannot increase the reading by more than 10 per cent. In a crude attempt to include their effect, the right-hand member of the above equation was divided by the rather arbitrarily chosen factor 1.06. We have again made the reasonable assumption of isotropic distribution. The material between the target and the electroscope is: (1) the target backing--0.010 inch of tantalum, (2) the target holder--0.008 inch of phosphor bronze, (3) the target tube--0.004 inch of German silver, and (4) the electroscope wall--0.030 inch of aluminum. On the basis of number of electrons this is equivalent to 0.819 gr cm^{-2} of aluminum which has a stopping power of 1.7 mev for the electrons in question[33]. However, the energy loss per electron in the heavier elements is smaller than in aluminum, and the value E_L = 1.3 mev was finally chosen; since this is fairly small compared with E_M its value does not influence the results seriously.

The (integrated) yield Y_π of each resonance may be obtained by graphical integration of the thin-target curve:

$$Y_{\pi} = \frac{1}{H} \frac{\mathcal{E}}{\mathcal{E}'} \int n_{\pi}(E)dE$$

where H, the thickness of the thin target is determined, as described above, from the gamma-ray observations.

The Yield of the Long-Range Alpha Particles

In the case of the alpha particle the assumption of isotropic distribution is not justified. Their angular distribution has been measured by Ellet, McLean, Young and Plain[34] at voltages from 0.27 to 0.44 mev. The distribution is practically independent of the proton energy in this range and is described by

$$I(\theta) = 1 + 0.77 \cos \theta + 0.17 \cos^2 \theta$$

in the center of mass coordinates. Lacking knowledge of the distribution at higher energies all of the calculations of yield from the alpha-particle intensity perpendicular to the proton beam were made on the basis of an isotropic distribution in laboratory coordinates. If, instead, the calculations were based on the above formula, the results would be increased by from 6 per cent, at the lower voltages, to 10 per cent, at the higher voltages. The calculation is made from obvious geometrical considerations.

As in the case of the electron pairs, the (integrated) yield of each resonance is obtained by integrating the thin-target curve and using the formula

$$Y_{\alpha} = \frac{1}{H} \frac{\mathcal{E}}{\mathcal{E}'} \int n_{\alpha}(E)dE$$

III. Results

The Excitation Functions

In Figure 7 are shown the excitation curves obtained on two occasions. For the second curve a thinner target was used. This accounts for the lower intensity and better resolution. It should be emphasized that the radiation designated as pairs is just that soft component absorbed by 1/8 inch of lead; in this experiment no further attempt was made to establish the identity of the radiation. As remarked above, the nature of this radiation has been established definitely only at 0.82 and 1.13 mev bombarding energy.

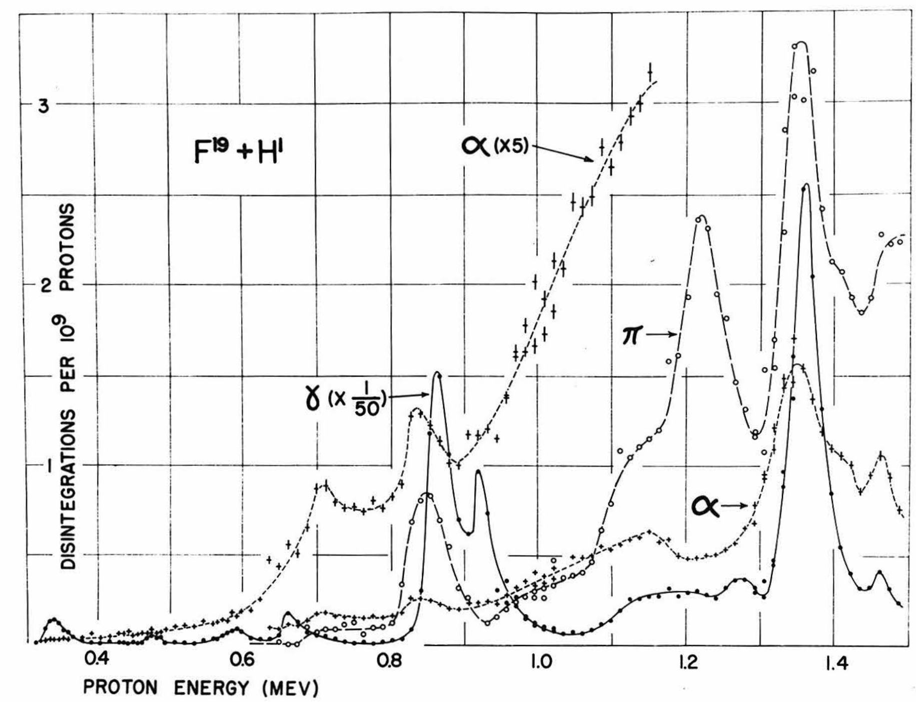
As stated above, no correction has been applied for undesired radiation from the tube itself, but some control runs were made with a clean tantalum target. The measurements are not very reproducible, but they show that the stray radiation does not effect the results appreciably except for the following, which might be of interest: The gamma-ray intensity in the neighborhood of 1.05 mev is very much smaller than shown; this fact was already known from the work of Bernet et al. Also, in the region from 1.1 to 1.3 mev the gamma-ray intensity is about 25 per cent less than that plotted.

Comparison with Previous Work

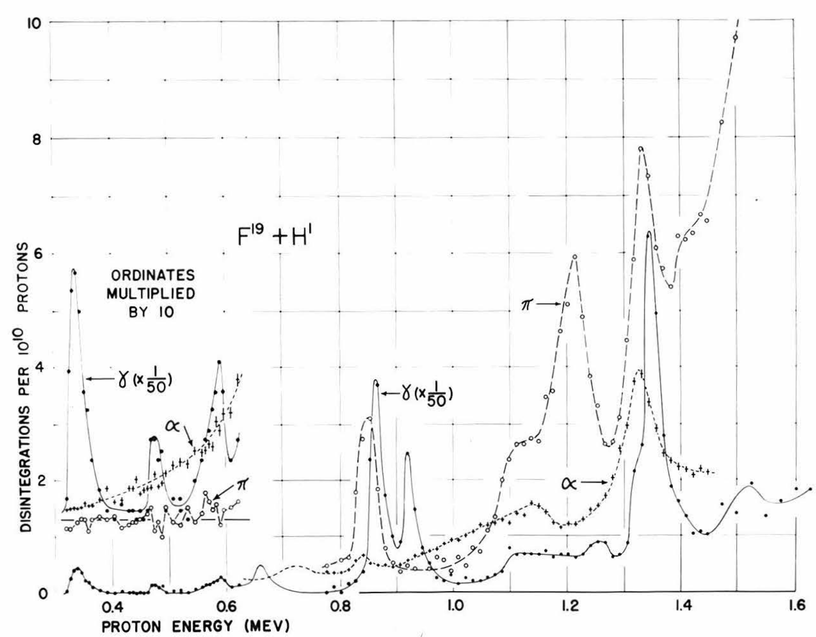
It will be observed that the gamma-ray curves are in good agreement with the work of Bernet et al, and the other investigators; the resolution is not as good as has been obtained before.

From data given by Tuve and Hafstad[35,20], Bethe[36] has estimated the yield of gamma rays from the 0.334 mev resonance with a CaF_2 target. The result is about 200 times smaller than that obtained in the present experiment. The calculation depends on the cross section at the 0.440 mev resonance in the production of gamma rays by proton bombardment of lithium. For this quantity

Fig. 7. The excitation functions. The curves marked γ, α and π refer to the gamma rays, long-range alpha particles and electron pairs, respectively. In some regions the upper graph represents a combination of four independent sets of data; the lower graph is based on a single set of data. The equivalent target thickness for 1 mev protons was 8 kev for the upper curve, 1.4 kev for the lower curve. In the lower diagram the upper end of the pair curve has been omitted; while its shape is not known accurately, it is certain that its sharp rise continues until at 1.62 mev the intensity is about 50 per cent greater than at 1.5 mev.



F19 + H1
α (x5)
π
γ (x 1/50)
α
DISINTEGRATIONS PER 10^9 PROTONS
PROTON ENERGY (MEV)



F19 + H1
ORDINATES MULTIPLIED BY 10
γ (x 1/50)
α
π
γ (x 1/50)
π
α
DISINTEGRATIONS PER 10^10 PROTONS
PROTON ENERGY (MEV)

Tuve and Hafstad estimate $10^{-27}cm^2$. They do not give the details of the calculation, but indicate that it is not very reliable. Their observations were also made with a Lauritsen electroscope. A comparison of observational data shows that the rate of deflection of their electroscope was equivalent to about one-fifth of that observed in the present experiment; a difference in electroscope sensitivities could account for this factor.

The long-range alpha-particle excitation reproduces the work of Burcham and Devons. In the higher energy range a new peak at 1.35 mev was found, and a broad, less conspicuous one at 1.14 mev is indicated in both sets of data. These peaks appear to be superimposed on a steady rise, as was already indicated at lower voltages. The yield of alpha particles agrees with the data of Henderson et al. Their work also showed a steady increase with bombarding voltage of alpha-particle production, but with a thick target and the somewhat inhomogeneous ion beam obtained from the cyclotron, they were unable to detect such details as the weak resonances.

Since the completion of the present experiment Van Allen and Smith[37] have announced the results of a direct measurement of the intensity of the short-range alpha particles produced at the 0.334 mev resonance; their figure is 20 per cent lower than the results given here for the corresponding gamma-ray intensity. This is good agreement, and constitutes additional evidence for the association of the gamma and alpha radiation and for the disintegration scheme described above.

The excitation function for pairs is in agreement with the earlier work of Fowler and Lauritsen, but better voltage control together with smaller separations on the voltage scale between observations permitted greater resolution. The importance of this improvement is made evident in the following section.

Simultaneous Resonances

In searching for simultaneous resonances in the different types of radiation it must be remembered that the maxima in the corresponding excitation curves may be displaced by an amount of the order of the width of the level[38].

There is a suggestion of a pair resonance at 0.75 mev which might coincide with the alpha-particle resonance which appears to be at 0.72 mev. The intensity of the pairs is so low that the structure cannot be established; it is quite possible that the rise in the curve is the result of a superposition of two or more resonances.

In the case of the pair and alpha-particle peaks at 0.85 and 0.83 mev, respectively, the structure is clearer. An inspection of the curves suggests that these peaks are slightly separated. A statistical study to determine the reality of the separation was made as follows: On a plot of the observations of each kind of radiation a reasonable curve was drawn to represent the background upon which the resonance is superimposed; this background intensity function was then subtracted from the observed intensity, and the centroid of the remaining intensity function was taken as the resonance energy. The separation was found to be 9. $\pm$ 5 kev; this uncertainty is the probable error. This must be compared with the (true) widths of the peaks which we have estimated as 15 kev. It will be observed that there is a gamma-ray peak lying only about 10 kev above the pair peak. However, this resonance cannot be associated with the pair resonance, for the curves clearly show that the latter is wider. This argument cannot be applied in the case of the long-range alpha-particle resonance, for its width is not easily estimated. However, it is separated by about 20 kev from the gamma-ray peak, and since Bernet et al have shown that the width of the latter is not more than 10 kev it seems unlikely that the same state is involved in both resonances.

The very prominent pair and long-range alpha-particle peaks near 1.35 mev appear to be coincident. A statistical investigation gives for the separation 6.5 $\pm$ 1.5 kev while the widths were both estimated to be 25. kev. The given uncertainty in the separation should not be regarded seriously, for the observations were taken at 12 kv intervals. Moreover, at these resonances it is difficult to know how to draw the background curves; for example, one may interpret the depression in the alpha-particle curve at 1.22 mev as the minimum between two resonances, but the pair resonance at this energy also suggests that the depression may be the result of an interference between the processes of emission of long- and short-range alpha particles. Again an obvious difference in width indicates that the nearby gamma-ray peak at 1.363 mev is not associated with the same stationary state. The similarity of the relative positions and widths of these three peaks to those of the three peaks discussed in the preceding paragraph is apparently a coincidence. The weak gamma-ray peak at 1.335 mev is not resolved by our data, but it is known from the work of Bernet et al to be still narrower than the 1.363 mev peak.

Professor Oppenheimer has pointed out that in the case of the long-range alpha particles one might expect a distortion and a displacement of the peaks due to an interference between the resonant process and the continuous process upon which it is superimposed. In the production of gamma rays and pairs the background is fairly small compared with the heights of the peaks, and the corresponding effect would be inappreciable.

We must not overlook the fact that there is a large possibility for an apparent coincidence between two different kinds of resonances which do not involve the same state of the intermediate nucleus. For example, if N_α

alpha-particle resonances, N_γ gamma-ray resonances and N_π pair resonances are distributed at random over an energy range W, the number of pairs of different kinds of resonances separated in energy by less than w is on the average

$$n = 2\frac{w}{W}(N_\alpha N_\gamma + N_\gamma N_\pi + N_\pi N_\alpha)$$

In the present case

$$N_\alpha = 4 \qquad N_\gamma = 8 \qquad N_\pi = 4$$

$$W = 1.5 - 0.3 = 1.2 \text{ mev}$$

and if we take

$$w = 0.010 \text{ mev}$$

we obtain

$$n = 1.2$$

Summary

In Table I are given the pertinent data for resonances below 1.5 mev. As may be seen by a comparison with the curves, some of the peaks tabulated are only vaguely indicated by the observations. In constructing the table, data on gamma rays given by Bernet et al have been used to fix the energy scale. Also, the figures for the widths of gamma-ray resonances are based on their data. The estimates of the width of the other resonances are very rough. They were made by subtracting from the observed widths the added width due to resolution difficulty. The observed width of gamma-ray lines known to be very sharp showed that this added width is about 5 kev.

Table I. Yields of the $F^{19} + H^1$ Reactions in Disintegrations per Proton from a Thick CaF_2 Target. In successive columns are recorded the proton energies for particular resonances or voltage regions, the radiation observed, the yield per 10^7 protons, the estimated true widths of the resonance peaks in kev, the stopping cross section in 10^{-15} ev·cm^2 of CaF_2 per fluorine atom, the proton wave-lengths in 10^{-12} cm, and values for $\omega\gamma = \omega\Gamma_p \Gamma_x / \Gamma$ in ev. The proton energies for the γ-ray resonances are those given by Bernet, Herb and Parkinson. The value zero for a resonance width indicates a width which is probably very small and certainly less than 10 kev. The great width of several peaks may be due to the superposition of two or more resonances. The nonresonant yields for pairs and alphas are the integrated yields to 1.5 mev below smooth curves drawn through the minima in the excitation functions for pairs and alphas.

E_P (mev)	R	$Y \times 10^7$	Γ (kev)	$\varepsilon \times 10^{15}$ ($ev \cdot cm^2$)	$\lambda \times 10^{12}$ (cm)	$\omega\gamma$ (ev)
0.334	γ	0.18_5	0	24.1	5.20	33
0.479	γ	0.05_2	0	18.4	4.34	10
0.589	γ	0.24_2	25	15.5	3.92	49
0.660	γ	0.46_2	0	14.2	3.70	96
0.6-0.8	π	0.013_2	--	--	--	--
0.72	α	0.007_5	15	13.6	3.54	1.6
0.84	α	0.006_1	15	12.3	3.30	1.4
0.85	π	0.10_5	15	12.1	3.26	24
0.862	γ	3.34	0	12.0	3.24	760
0.927	γ	2.21	0	11.5	3.12	520
0.9-1.2	α	0.06_4	--	--	--	--
1.14	π	0.07_8	30	10.0	2.81	20
1.22	π	0.20_5	30	9.5	2.72	53
1.1-1.3	γ	3.03	--	--	--	--
1.35	α	0.13_6	25	8.8	2.59	36
1.35	π	0.19_5	25	8.8	2.59	51
1.335	γ	1.25	0	8.9	2.60	330
1.363	γ	7.71	10	8.7	2.57	2020
Nonresonant	π	1.18	--	--	--	--
	α	0.69	--	--	--	--
Total						
to 1.0	γ	6.50	--	--	--	--
to 1.5	γ	22.0	--	--	--	--
"	π	1.78	--	--	--	--
"	α	0.90	--	--	--	--

IV. Discussion

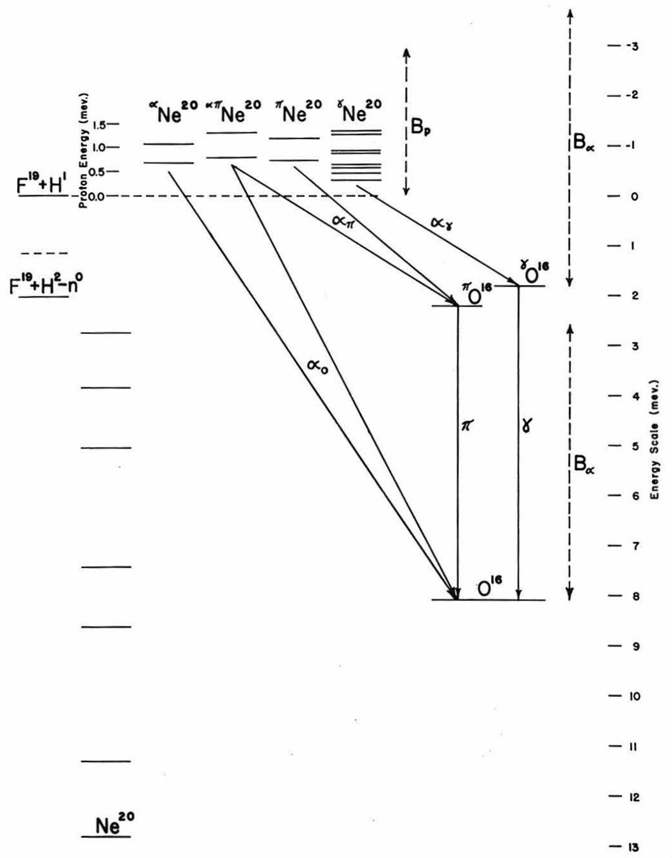
The Character of the States

An energy-level diagram is shown in Figure 8. The relative positions of the ground states are determined from the masses. The levels ${}^{\gamma}O^{16}$ and ${}^{\pi}O^{16}$ are plotted from a knowledge of the gamma-ray and pair energies. The first six excited states in neon are those found by Bonner. The higher levels are those found in the present and similar experiments.

If we accept the evidence discussed above as indicating simultaneous resonances in the production of pairs and long-range alpha particles, the simplest procedure is to interpret this as a branching process in the decay of certain states of Ne^{20}. According to Oppenheimer and Schwinger this is reasonable; at energies above 1 mev the effect of the Coulomb barrier is unimportant for both the long- and short-range alpha particles. Following this interpretation the excited states of Ne^{20} produced by proton bombardment of fluorine were classified in four groups, according to the manner of their decay, as indicated in the diagram. As mentioned before, this conclusion implies the parity of the state ${}^{\pi}O^{16}$ is even, and that it is possible to account for the pair emission through electromagnetic forces.

To explain the appearance of short-range alpha particles leading to gamma emission rather than the long-range alpha particles we assume that the states ${}^{\gamma}Ne^{20}$ and ${}^{\gamma}O^{16}$ have odd parity and even angular momentum, or vice-versa. Then the emission of both the short-range alpha particle leading to pairs and the long-range alpha particle are forbidden. In particular, the simplest assumption is that the states ${}^{\gamma}O^{16}$ and ${}^{\gamma}Ne^{20}$ are of the type (1+) (angular momentum 1, and even parity) and that the states ${}^{\alpha}Ne$, ${}^{\pi}Ne$ and ${}^{\alpha\pi}Ne$ are of the type (0+). These two different kinds of states of the neon nucleus

Fig. 8. Energy Level Diagram. The levels of Ne^{20} are those observed in this and similar experiments. The levels of Ne^{20} plotted in the column above the ground state of Ne^{20} are those found by Bonner. The short dotted line in the left hand column indicates his bombarding energy; the region between here and the level $F^{19} + H^{1}$ is unexplored. The transitions marked α_0 are described in Reaction (1), those marked α_γ and γ in Reaction (5), and those marked α_π and π in Reaction (7). The arrows marked B_p and B_α show the barrier heights for protons and alpha particles.



F19+H1
F19+H2-n0
Ne20
Proton Energy (mev.)
1.5
1.0
0.5
0.0
αNe20
απNe20
πNe20
γNe20
Bp
Bα
α0
απ
αγ
πO16
γO16
O16
π
γ
Energy Scale (mev.)
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
13

might be formed by the two ways of adding the angular momenta of the fluorine nucleus and an s-proton.

Remaining Difficulties

However, the picture is far from complete. No explanation has been advanced for the irregular variation in intensity of the various gamma-ray levels. More puzzling still is the very high probability of gamma-ray production compared with the other two processes. All three processes depend on the emission of an alpha particle from the neon nucleus, and the effect of the barrier favors the long-range alpha particles; on the other hand, one expects the statistical distribution of energy among the nuclear particles to act in the reverse direction, for the probability that an alpha particle has one-third (approximately) of the excitation energy should be much greater than the probability that it has all of the excitation energy. The three types of states ${}^{\alpha}Ne^{20}$, ${}^{\pi}Ne^{20}$ and ${}^{\alpha\pi}Ne^{20}$ are differentiated on the basis of the relative intensities of the long- and short-range alpha particles which result from their decay, but no explanation for this difference in behavior has been proposed.

Of course it would be possible to account for the relative intensities of the radiations by assigning appropriate values of angular momentum to the stationary states and to the orbits of the captured and ejected particles, but the values of angular momenta become so large that the procedure seems entirely arbitrary. Probably some new selection rule must be invoked[39].

Comparison with an Alpha-Particle Model of the Oxygen Nucleus

Dennison[40] has calculated the positions of the low-lying levels in O^{16}, taking as a model four particles (alpha particles) oscillating under the influence of harmonic forces about their equilibrium positions at the vertices of a regular tetrahedron. The model provides an excited (0+) level to be identified as the state $^{\pi}O^{16}$. There is no low-lying (1+) level, but there is a (2-) level which will serve as the state $^{\gamma}O^{16}$. This implies that the short-range alpha particle preceding the gamma ray is emitted with one unit of orbital angular momentum. There is also a (3-) state at 4.1 mev; this, of course, disrupts the entire scheme. If one arbitrarily chooses a value for the nuclear radius, upon which the energy of this level depends, 25 per cent lower than the values derived from alpha decay or the packing effect due to the replacement of a proton with a neutron, this level is raised to 5.1 mev, where the small available energy suppresses transitions to this state from the states $^{\pi}O^{16}$ and $^{\gamma}O^{16}$. With this assumption and the known positions of the other two levels, the force constants of the model are evaluated and the positions of other low-lying levels are determined. Transitions to one of these other states of oxygen with the emission of an alpha particle is either forbidden by the angular momentum—parity selection ~~rate~~ rule, or is rendered improbable by the requirement of an orbital angular momentum of two or more units with low kinetic energy.

References

1. Cockroft, Walton: Proc. Roy. Soc., A137, 229 (1932).
2. Oliphant, Rutherford: Proc. Roy. Soc., A141, 259 (1933).
3. Henderson, Livingston, Lawrence: Phys. Rev., 46, 38 (1934).
4. Burcham, Smith: Proc. Roy. Soc., A166, 176 (1938).
5. Burcham, Devons: Proc. Roy. Soc., A173, 555 (1939).
6. Livingston, Bethe: Rev. Mod. Phys., 9, 3 (1937).
7. McMillan: Phys. Rev., 46, 325 (1934).
8. McMillan: Phys. Rev., 46, 868 (1934).
9. Crane, Delsasso, Fowler, Lauritsen: Phys. Rev., 46, 531 (1934).
10. Delsasso, Fowler, Lauritsen: Phys. Rev., 51, 391 (1937).
11. Delsasso, Fowler, Lauritsen: Phys. Rev., 51, 527 (1937).
12. Halpern, Crane: Phys. Rev., 55, 258 (1939).
13. Curran, Dee, Petržílka: Proc. Roy. Soc., A169, 269 (1938).
14. Dee, Curran, Strothers: Nature, 143, 759 (1939).
15. Gaerttner, Crane: Phys. Rev., 52, 582 (1937).
16. Halpern, Crane: Phys. Rev., 55, 260 (1939).
17. Lauritsen, T.: Thesis (Ph. D) Calif. Inst. of Tech. (1939).
18. Lauritsen, Fowler, Lauritsen: Phys. Rev., 56, 858 (1939) (A). Some of the results mentioned have not been published.
19. Hafstad, Heydenburg, Tuve: Phys. Rev., 49, 866 (1936) (A).
20. Hafstad, Heydenburg, Tuve: Phys. Rev., 50, 504 (1936).
21. Herb, Kerst, McKibben: Phys. Rev., 51, 691 (1937).
22. Bernet, Herb, Parkinson: Phys. Rev., 54, 398 (1938).
23. McLean: Thesis (Ph. D) Calif. Inst. of Tech. (1939).
24. McLean, Becker, Fowler, Lauritsen: Phys. Rev., 55, 797 (1939).
25. Burcham, Smith: Nature, 143, 796 (1939).

26. Bonner: Proc. Roy. Soc., A174, 339 (1940).

27. Fowler, Lauritsen: Phys. Rev., 56, 840 (1939).

28. Oppenheimer, Schwinger: Phys. Rev., 56, 1066 (1939).

29. Laurence: Canadian Jour. of Research., A15, 67 (1937).

30. Heitler: Quantum Theory of Radiation.

31. Lauritsen: Am. Jour. of Roent. and Rad. Therapy, 30, 380 (1933).

32. Pasadena meeting of Amer. Phys. Soc., Dec., 1940 (1). A description of their calculations will also appear shortly in the Phys. Rev.

33. Rasetti: Elements of Nuclear Particles.

34. Ellet, McLean, Young, Plain: Phys. Rev., 57, 1083 (1940) (A).

35. Hafstad, Tuve: Phys. Rev., 48, 306 (1935).

36. Bethe: Rev. Mod. Phys., 9, 69 (1937).

37. Chicago meeting of Amer. Phys. Soc., Nov., 1940 (15).

38. Breit: Science, 91, 419 (1940) (A).

39. Streib, Fowler, Lauritsen: Phys. Rev., 58, 187 (1940) (A).

40. Dennison: Phys. Rev. 57, 454 (1940).