Gamma-Ray Spectrometer Measurements of Fluorine and Lithium under Proton Bombardment

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The spectra of the gamma-radiation emitted by lithium and fluorine under proton bombardment have been investigated with a spectrometer which measures the total energy of electron pairs produced in a thin radiator exposed to the gamma-radiation. A long-suspected 14.8-Mev gamma-ray line from the 440-kev resonance in lithium has been clearly resolved from the well-known sharp line at 17.6 Mev. The gamma-radiation from fluorine has been found to consist of two lines at 6.13±0.06 and 6.98±0.07 Mev, rather than a single line as previously believed. Possible variations in the positions and in the relative intensities of the two lines of each spectrum, with changes in the proton energy, have been investigated by using protons of energies approximately 0.45, 0.7, and 1.15 Mev from the Cornell cyclotron. The gamma-ray spectrometer used in these measurements is described, and a discussion given of the factors limiting its resolution. The resolution is such that the observed width at half-maximum of a sharp gamma-ray line is approximately 5.5 percent of its energy.

I. INTRODUCTION

THE methods which have been used for the determination of gamma-ray energies in the region above 2 or 3 Mev are exemplified by the experiments which have been performed to measure the spectra of the gamma-radiation emitted by lithium and fluorine under proton bombardment. From early measurements of the absorption coefficient in different materials, McMillan[1] obtained a value 5.4 Mev for the quantum energy of the fluorine radiation; and Crane, Delsasso, Fowler, and Lauritsen[2] obtained values of 5.6 and 6.3 Mev for the fluorine and lithium gamma-rays, respectively.

In 1935, Crane, Delsasso, Fowler, and Lauritsen[3] reported at least eleven lines from lithium between 2 and 16 Mev, based on measurements of the spectrum of recoil electrons in a cloud chamber. By a similar method, Gaerttner and Crane[4] found large peaks at 11.5, 14.5, and 17 Mev, for lithium, and two lines for fluorine, at 4 and 5.7 Mev. In 1937, Delsasso, Fowler, and Lauritsen[5] pointed out sources of error in their previous work and gave results for the lithium spectrum, obtained by measuring the total energy of electron pairs ejected from a thin lead plate in a cloud chamber. Their curve shows a single peak with a maximum at 17.1 Mev. From a marked asymmetry in the peak, they conclude that in addition to the main line at 17.1±0.5 Mev, there are one or more additional lines near 14 Mev, but none between 2 and 10 Mev.

By the same method, Delsasso, Fowler, and Lauritsen[6] measured the fluorine spectrum and obtained a single symmetrical line at 6.0±0.2 Mev.

Magnetic spectrometers have been used by Dee, Curran, and Strothers[7] to measure the fluorine radiation, and by McDaniel, Von Dardel, and Walker[8] to measure the lithium spectrum, but thus far no improvements have been reported over the cloud-chamber results of Delsasso, Fowler, and Lauritsen.

The high energy gamma-rays from lithium are believed to arise from the reaction:

$$Li^7+H^1\rightarrow Be^{8*}\rightarrow Be^8+h\nu. \quad (1)$$

The 17.6-Mev gamma-ray is emitted when the Be^8 nucleus is left in its ground level, whereas

[1] E. McMillan, Phys. Rev. **46**, 325, 868 (1934).
[2] H. R. Crane, L. A. Delsasso, W. A. Fowler, and C. C. Lauritsen, Phys. Rev. **46**, 531 (1934).
[3] H. R. Crane, L. A. Delsasso, W. A. Fowler, and C. C. Lauritsen, Phys. Rev. **48**, 125 (1935).
[4] E. R. Gaerttner and H. R. Crane, Phys. Rev. **52**, 582 (1937).
[5] L. A. Delsasso, W. A. Fowler, and C. C. Lauritsen, Phys. Rev. **51**, 391 (1937).
[6] L. A. Delsasso, W. A. Fowler, and C. C. Lauritsen, Phys. Rev. **51**, 527 (1937).
[7] P. I. Dee, S. C. Curran, and J. E. Strothers, Nature **143**, 759 (1939); S. C. Curran, P. I. Dee, and J. E. Strothers, Proc. Roy. Soc. **A174**, 546 (1940).
[8] B. D. McDaniel, Guy Von Dardel, and R. L. Walker, Phys. Rev. **72**, 985 (1947).

lower energy gamma-rays may be expected if the Be^8 is left in an excited state.[5]

Early measurements of the excitation curve for the lithium radiation showed resonances near 450 kev and 850 kev.[9–11] Hafstad, Heydenburg, and Tuve[12] showed that the 440-kev resonance is very narrow, with a width of about 11 kev. They did not confirm the existence of the higher energy resonance. In 1940, Hudson, Herb, and Plain[13] found that radiation from the higher resonance has an energy of only 459 kev, and interpreted it as arising from the excitation of the 455-kev level in Li^7 by inelastic scattering of the protons. They also found that above the sharp 440-kev resonance the yield of high energy gamma-rays from lithium does not drop to zero but to a small value which remains almost constant up to a proton energy of about 1.6 Mev. This result has been confirmed in a recent investigation of the excitation curve by Bonner and Evans.[14]

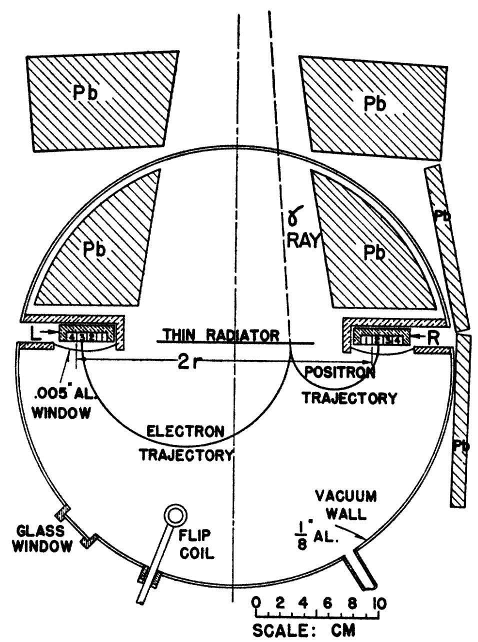

FIG. 1. Diagram of the spectrometer—a horizontal section through the gap of the large magnet which produces a magnetic field normal to the plane of the paper. The vertical height of the gap is 4 inches. Coincidences are observed between any one of the four Geiger counters at the left labeled L and any one of the four on the right labeled R. The gamma-ray source (cyclotron target) was 60 cm from the radiator in the present experiments.

In addition to the gamma-rays emitted by lithium under proton bombardment, alpha-particles of 8.4-cm range are produced by the reaction:[15,16]

$$Li^7+H^1\rightarrow Be^{8*}\rightarrow 2He^4. \quad (2)$$

The excitation curve for these long-range alpha-particles shows a smooth Gamow type increase in alpha-particle yield with increasing proton energy,[12,15–19] with no sign of a resonance at 440 kev. As is well known, the sharpness of the 440-kev gamma-ray resonance is explained by the action of rigid selection rules preventing the disintegration of the Be^{8*} "gamma-ray level" at 17.6 Mev into two alpha-particles.[5,12,20,21]

The origin of the gamma-radiation from fluorine has been the subject of much speculation, but the reaction is now believed to be:

$$\begin{aligned} F^{19}+H^1&\rightarrow Ne^{20*}\rightarrow O^{16*}+He^4+Q,\\ O^{16*}&\rightarrow O^{16}+h\nu. \end{aligned} \quad (3)$$

The simple capture reaction analogous to (1):

$$F^{19}+H^1\rightarrow Ne^{20*}\rightarrow Ne^{20}+h\nu \quad (4)$$

was shown to be incorrect since no gamma-rays of the expected energy, 13 Mev, were observed.[1,4,6] Successive emission of two gamma-rays of about half the total energy was suggested by Burcham and Smith,[22] since they could not find the low energy alpha-particles expected from reaction (3). However, this was ruled out by Dee, Curran, and Strothers,[7] who measured coincidences between gamma-rays, and found less than 1 percent of the number expected if two suc-

[9] L. R. Hafstad and M. A. Tuve, Phys. Rev. **48**, 306 (1935).
[10] L. H. Rumbaugh and L. R. Hafstad, Phys. Rev. **50**, 681 (1936).
[11] R. G. Herb, D. W. Kerst, and J. L. McKibben, Phys. Rev. **51**, 691 (1937).
[12] L. R. Hafstad, N. P. Heydenburg, and M. A. Tuve, Phys. Rev. **50**, 504 (1936).
[13] C. M. Hudson, R. G. Herb, and G. J. Plain, Phys. Rev. **57**, 587 (1940).
[14] T. W. Bonner and J. E. Evans, Phys. Rev. **73**, 666 (1948).
[15] J. D. Cockcroft and E. T. S. Walton, Proc. Roy. Soc. **A137**, 229 (1932).
[16] M. L. E. Oliphant, B. B. Kinsey, and Lord Rutherford, Proc. Roy. Soc. **A141**, 722 (1933).
[17] M. C. Henderson, Phys. Rev. **43**, 98 (1933).
[18] R. G. Herb, D. B. Parkinson, and D. W. Kerst, Phys. Rev. **48**, 118 (1935).
[19] N. P. Heydenburg, C. T. Zahn, and L. P. D. King, Phys. Rev. **49**, 100 (1936).
[20] H. A. Bethe, Rev. Mod. Phys. **9**, 205, 211 (1937).
[21] F. Kalckar, J. R. Oppenheimer, and R. Serber, Phys. Rev. **52**, 279 (1937).
[22] W. E. Burcham and C. L. Smith, Proc. Roy. Soc. **A168**, 176 (1938).

cessive gamma-rays were emitted. They also obtained evidence against a reaction similar to (3):

$$F^{19}+H^1\rightarrow Ne^{20**}\rightarrow Ne^{20*}+h\nu,\quad Ne^{20*}\rightarrow O^{16}+He^4+Q, \tag{5}$$

by showing that the gamma-ray energy does not change with proton energy for protons of 330, 670, and 860 kev. This result was confirmed by Lauritsen, Lauritsen, and Fowler,[23] who concluded from cloud-chamber measurements that the gamma-radiation has the same average energy for protons of energy 334, 950, and 1400 kev on "semithick" targets.

The low energy alpha-particles expected from reaction (3) were found by Burcham and Smith,[24] and by McLean, Becker, Fowler, and Lauritsen.[25] Burcham and Devons[26] showed that the energy of these alpha-particles increases with proton energy by about the amount to be expected, and that their excitation function follows closely that of the gamma-rays, from 300 to 900 kev. A detailed study of these low energy alpha-particles at different proton energies was made by Becker, Fowler, and Lauritsen,[27] who obtained a value $Q=1.81\pm0.04$ Mev for reaction (3).

The excitation function for the gamma-rays emitted by fluorine under proton bombardment is a series of many sharp resonances, the lowest being at 334 kev.[14,28–30] The narrow widths of these resonances, most of them under 10 kev,[30,14] is again explained by selection rules which prohibit or retard the disintegration of the excited Ne^{20} nucleus by long-range alpha-particle emission.[21,28,20]

The production of such alpha-particles of 6-cm range was observed by Henderson, Livingston, and Lawrence,[31] who obtained a smooth Gamow

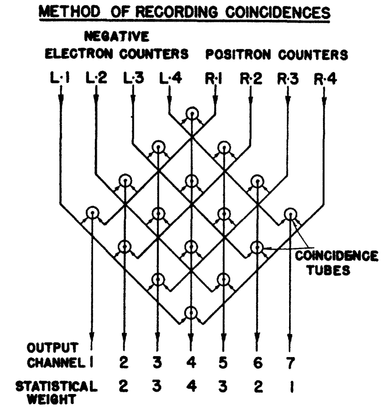

FIG. 2. Schematic diagram of the coincidence circuit. Coincidences from the sixteen possible combinations of one positron counter and one negative electron counter are grouped into seven different energy output channels according to the separation of the counters. The "statistical weight" of each channel is simply the number of individual counter pairs feeding it.

type excitation function for this reaction:

$$F^{19}+H^1\rightarrow Ne^{20*}\rightarrow O^{16}+He^4+Q. \tag{6}$$

Later, broad resonances were found in the thin target excitation curve for these long-range alpha-particles,[26,29] but these resonances are not correlated with those observed for the gamma-rays.

In addition to the long-range alpha-particles and gamma-rays emitted by fluorine under proton bombardment, electron pairs of total energy 5.9 ± 0.5 Mev were found by Fowler and Lauritsen[32] in 1939. The excitation function for these pairs[29,30,32] exhibits resonances which differ from the gamma-ray resonances, so that the pairs cannot be the result of ordinary pair internal conversion of the gamma-rays.[32] They are ascribed to the reaction:

$$F^{19}+H^1\rightarrow Ne^{20*}\rightarrow O_\pi^{16*}+He^4+Q,\quad O_\pi^{16*}\rightarrow O^{16}+\pi. \tag{7}$$

The oxygen pair level, O_π^{16*}, is assumed to have $J=0$, and to have no non-zero levels below it, so that the emission of a single quantum is forbidden.[32,33] The energy of the pairs has been measured with a magnetic spectrograph by

[23] T. Lauritsen, C. C. Lauritsen, and W. A. Fowler, Phys. Rev. **59**, 241 (1941).
[24] W. E. Burcham and C. L. Smith, Nature **143**, 795 (1939).
[25] W. B. McLean, R. A. Becker, W. A. Fowler, and C. C. Lauritsen, Phys. Rev. **55**, 796 (1939).
[26] W. E. Burcham and S. Devons, Proc. Roy. Soc. **A173**, 555 (1939).
[27] R. A. Becker, W. A. Fowler, and C. C. Lauritsen, Phys. Rev. **62**, 186 (1942).
[28] E. J. Bernet, R. G. Herb, and D. P. Parkinson, Phys. Rev. **54**, 398 (1938).
[29] J. F. Streib, W. A. Fowler, and C. C. Lauritsen, Phys. Rev. **59**, 253 (1941).
[30] W. E. Bennett, T. W. Bonner, C. E. Mandeville, and B. E. Watt, Phys. Rev. **70**, 882 (1946).
[31] M. C. Henderson, M. S. Livingston, and E. O. Lawrence, Phys. Rev. **46**, 38 (1934).
[32] W. A. Fowler and C. C. Lauritsen, Phys. Rev. **56**, 840 (1939).
[33] J. R. Oppenheimer and J. S. Schwinger, Phys. Rev. **56**, 1066 (1939).

Tomlinson,[34] who found a total energy of 6.0±0.2 Mev.

The results of the experiments to be described below confirm the essential features of the ideas outlined above as to the origin of the gamma-radiation from lithium and fluorine under proton bombardment. It will only be necessary to propose two gamma-ray levels of O^{16} for reaction (3), in order to account for the two gamma-rays observed from fluorine.

II. APPARATUS

A. The Gamma-Ray Spectrometer

The spectrometer used in the present experiments is based upon the same principles as one used a year ago by McDaniel, Von Dardel, and Walker.[8] It performs a magnetic analysis of pairs produced by the gamma-rays in a thin radiator. A diagram of the apparatus is shown in Fig. 1, which is a horizontal cross section through the gap of a large magnet used to produce a magnetic field perpendicular to the plane of the paper.

Electron pairs are produced in the thin radiator by high energy gamma-rays from the cyclotron target or other source. The two particles of a pair are emitted in directions which do not deviate greatly from that of the incident gamma-ray, and follow circular paths in the magnetic field, as indicated schematically in Fig. 1. A fraction of the positrons produced will enter one of the four Geiger counters on the right labeled R in the figure, and, similarly, a fraction of the negative electrons will have radii of curvature such as to enter one of the four Geiger counters on the left labeled L. Coincidences are observed between any one of the four positron counters and any one of the four electron counters, giving, in all, sixteen possible coincidence pairs. If an electron pair produces a coincidence between two counters whose separation is $2r$ (for example, counters $L3$ and $R2$ in Fig. 1), then the *sum* of the radii of curvature of the positron and that of the electron (r_1 and r_2) is known and is equal to r. From the well-known relation between the momentum of an electron and its radius of curvature in a magnetic field, the sum of the momenta of the positron and the electron is then

$$p_1+p_2=300H(r_1+r_2)=300Hr. \tag{8}$$

[34] E. P. Tomlinson, Phys. Rev. **60**, 159A (1941).

If H is in gauss and r in cm, p will be in electron volts.* The energy of the quantum which produced the pair will be equal to the total energy of the two particles, or

$$k=E_1+E_2=(p_1^2+\mu^2)^{\frac{1}{2}}+(p_2^2+\mu^2)^{\frac{1}{2}}.$$

If $p_1 \gg \mu$ and $p_2 \gg \mu$ then

$$k\approx 300Hr[1+(\mu^2/2p_1p_2)]. \tag{9}$$

The "correction term," $\mu^2/2p_1p_2$, depends upon the individual momenta, p_1 and p_2, and thus depends upon the particular position along the radiator where the pair originated. However, if $k \gg \mu$, it is easily seen that this term is small, and that its dependence on the place of origin of the pair is actually very slight. This may be seen by calculating the correction term, using the approximation $p_1+p_2\approx k$, for a pair produced at the center of the radiator, and for one produced at its edge. If a coincidence is observed for a pair produced at the center of the radiator, $(\mu^2/2p_1p_2)=(2\mu^2/k^2)$. If the pair were produced at the edge of the radiator, then for a radiator of the width actually used, $(\mu^2/2p_1p_2)=(8/3)(\mu^2/k^2)$. Using the average of these two results we may write

$$k=300Hr[1+(7/3)(\mu^2/k^2)], \tag{10}$$

and the relative error caused by variations in the correction term for pairs originating at different places along the radiator will be less than $\frac{1}{3}(\mu^2/k^2)$. This is 0.9 percent for a 3-Mev gamma-ray, 0.2 percent for a 6-Mev gamma-ray, and much smaller for the 17.6-Mev gamma-ray from lithium.

The above considerations show that, for a given value of the magnetic field, all coincidences in a given pair of counters are produced by gamma-rays of essentially a single energy. Furthermore, all pairs of counters having the same separation are sensitive to gamma-rays of the same energy, and their data may be recorded together, as will be described later.

In the above discussion we have obviously neglected certain effects which will tend to reduce the resolving power of the spectrometer. Chief among these are the finite width of the Geiger

* We shall use energy units for both momentum and mass. The momentum of a light quantum is then equal to its energy and both will be denoted by k. Cf. Heitler, *Quantum Theory of Radiation* (Oxford University Press, London, 1936).

TABLE I. Effect of electron scattering in Al window.

Electron energy (Mev)	$(\frac{1}{2}\langle\Theta^2\rangle_{Av})^{\frac{1}{2}}$ (radians)	δ (cm)	δ/w relative increase in effective counter width (%)
10	0.17	0.14	17
5	0.34	0.26	32
2	0.9	0.9	110

TABLE II.

Radiator	Thickness (g/cm^2)	Thickness (radiation lengths)[36]	$\langle\Delta k/k\rangle_{Av}$ $k=17.6$ Mev (%)	$\langle\Delta k/k\rangle_{Av}$ $k=6.1$ Mev (%)
0.003″ Al	0.0211	0.00080	0.13	1.04
0.002″ Cu	0.0466	0.0035	0.55	4.5
0.004″ Cu	0.0888	0.0067	1.06	8.7
0.003″ Pb	0.0846	0.0143	2.3	—

counters and the fact that the electrons are not emitted in a direction exactly normal to the surface of the radiator, but with a spread of angles from this normal. These and other effects will be investigated later in discussing the resolution obtainable, but it may be mentioned now that the 180-degree focusing utilized in the spectrometer is a powerful aid in reducing the effects of the spread in angles of emission of the electrons.

The Geiger counters used for measuring coincidences caused by pairs are of square cross section about 8 mm wide. Each row of four counters was constructed by milling four slots in a brass plate, separated by $\frac{1}{32}$-in. walls. The front face was then covered with 0.002-in. brass shim stock. Since the counters are 6 inches long, and the magnet gap only 4 inches high, the pole pieces are provided with slots to receive the counters. The pole pieces form the lids of a vacuum chamber whose $\frac{1}{8}$-in. aluminum walls are indicated in Fig. 1. The counters are not located within the vacuum itself, but are separated from it by a thin 0.005-in. aluminum window through which the electrons must pass. The height of this window, 8.3 cm, determines the useful length of the counters, and is sufficiently high to give a good counting rate even with weak gamma-ray intensities.

The area of the radiators used was 6.3×12.8 cm. The thickest radiator was of 0.004-in. copper and the thinnest of 0.003-in. aluminum. Two different radiators can be supported on rotating frames in the vacuum chamber in such a way that either one may be placed in position or removed from the gamma-ray beam, as desired, without breaking the vacuum.

The reason for evacuating the chamber of the spectrometer is not only to avoid scattering of the pair electrons by air, but also to avoid the production of pairs in the air. The latter effect would not always be entirely negligible since radiators as thin as 0.003-in. aluminum have been used and this is equivalent to only 25 cm of air for the production of pairs. Recoil electrons and pairs are produced in the front wall of the vacuum chamber, of course, but these are prevented from reaching the counters by the "clearing field" in front of the radiator.

The counters are shielded from direct gamma-rays from the source by the lead blocks shown in Fig. 1. There is also some lead shielding in the vertical direction, which is not shown, and which shields most of the top and bottom of the chamber from the direct gamma-rays. In addition, the $\frac{1}{2}$-inch lead plates shown in Fig. 1 were placed just outside the chamber by the side of the positron counters. This was found to cut down the "singles" counting rate of these counters by a large factor—presumably by preventing recoil electrons from the air and elsewhere outside the chamber from being deflected into the positron counters by the magnetic field.

It is obviously important that the magnetic field be uniform throughout the region which is traversed by the pair electrons. Since the gap height is rather large, the pole faces were supplied with "Rose shims"[35] to delay the falling off of the field near the edge of the magnet. A map of the field made with small search coils showed that the field was uniform within the accuracy of measurement, about 0.2 percent, from the center of the magnet out to a radius slightly larger than that given by the outside wall of the counters. In addition, the very local disturbances to the field caused by the slots in the pole pieces for holding the counters were measured to make sure they were negligible.

This description of the spectrometer may be concluded by giving an approximate value for its sensitivity in detecting gamma-rays. The counting efficiency has been calculated from the cross

[35] M. E. Rose, Phys. Rev. 53, 715 (1938).

TABLE III. Summary of measurements.

Figure	Target	Proton energy (Mev)	Energy range investigated (Mev)	Radiator (see Table II)
3	Thick Li	1.15	3–19	0.002″ Cu
4	Thin Li (150 kev)	0.46	12–19	0.002″ Cu
4	Thick Li	0.75	10–19	0.002″ Cu
4	Thick Li	1.15	10–19	0.002″ Cu
5	Thin Li (150 kev)	0.46	11–19	0.004″ Cu
5	Thin Li (70 kev)	1.15	11–19	0.004″ Cu
6	Thick CaF_2	1.15	3–18	0.002″ Cu
7	Thick CaF_2	1.15	4.8–7.8	0.003″ Al
7	Thick NaF	1.15	4.8–7.8	0.003″ Al
8	Thick NaF	0.45	4.8–7.8	0.002″ Cu
8	Thick NaF	0.70	4.8–7.8	0.002″ Cu
8	Thick CaF_2	1.15	4.8–7.8	0.002″ Cu

section for pair production in the radiator material and from the geometry of the apparatus. The result is that the peak counting rate per single counter pair, for 17.6-Mev gamma-rays and a 0.002-in. Cu radiator (0.0035 radiation lengths),[36] is approximately 10^{-7} times the rate of gamma-emission from the source. The source is assumed to be 60 cm from the radiator, as it was in the present experiments.

At lower gamma-ray energies the effective sensitivity decreases both because the cross section for pair production decreases, and because thinner radiators must be used to maintain the same resolution. At energies below 5 or 6 Mev the resolution becomes unavoidably worse than that attainable at higher energies, and below 3 Mev the spectrometer would not be very useful.

B. Recording Equipment

Pulses from each of the eight Geiger counters in the spectrometer are given one stage of amplification, and then used to trigger a multivibrator which produces an approximately square, negative pulse about 1.5 microseconds long. This length determines the resolving time against accidental coincidences. The negative pulse from each counter channel is then fed into each of four Rossi cathode follower type coincidence tubes which measure coincidences between this counter and any one of the four on the opposite side of the spectrometer. This arrangement is shown by the schematic diagram of Fig. 2, as is also the manner of grouping the output pulses from the coincidence tubes into seven different channels according to the distance of separation of the two counters giving the coincidence. For a given magnetic field these seven channels count electron pairs in seven different energy intervals, according to the relation (10). The number of pulses in each of the seven output channels is counted by a scale of four, using the Higinbotham circuit[37] and a mechanical recorder.

The seven output channels have different statistical weights as shown in Fig. 2, according to the number of counter pairs having the appropriate separation. Thus only one counter pair ($L1+R1$) has the smallest separation, and coincidences from this pair are counted alone in the lowest energy channel, No. 1. On the other hand, four counter pairs ($L4+R1$, $L3+R2$, $L2+R3$, $L1+R4$) have the separation corresponding to the central channel, No. 4.

In addition to recording coincidences, the individual "singles" counting rates of one of the positron counters, and one of the negative electron counters, were measured in order to be able to calculate the accidental coincidence rate. The rate of accidental coincidences was 0.1 to 0.3 percent of the peak counting rate in typical cases, and no correction for it has been made in any of the data.

C. Magnetic Field Measurement

The magnetic field in the spectrometer was measured by means of a flip coil and fluxmeter calibrated with a standard mutual inductance. A null method was used in order to obtain high sensitivity. This method is capable of high relative accuracy, but the absolute accuracy is limited by that of the mutual inductance and by possible uncertainties in the effective area of the flip coil. For this reason an independent absolute field calibration was obtained by a nuclear induction experiment in which the Larmor frequency of precession of protons in the magnetic field of the spectrometer was measured. From the accurately known value of the gyromagnetic ratio of the proton,[38] and the observed Larmor frequency, the field strength may be found.[39] From measure-

[36] See, for example, B. Rossi and K. Greisen, Rev. Mod. Phys. 13, 240 (1941).

[37] W. A. Higinbotham, J. Gallagher, and M. Sands, Rev. Sci. Inst. 18, 706 (1947).

[38] S. Millman and P. Kusch, Phys. Rev. 60, 91 (1941).

[39] F. Bloch, Phys. Rev. 70, 460 (1946); F. Bloch, W. W. Hansen, and M. Packard, Phys. Rev. 70, 474 (1946); E. M.

ments at magnetic fields of 1650, 2000, 2350, and 2820 gauss, it was found that the calibration of the flip coil equipment should be changed by only 0.5 percent. We are indebted to Mr. E. Sharp for making this absolute field calibration.

D. Targets and Monitors

For the fluorine measurements, thick targets of CaF_2 and of NaF were used. These were prepared by mixing CaF_2 powder in distilled water, or disolving NaF, then pouring the mixture or solution into a recessed area in a brass target backing, and evaporating away the water. For some of the lithium measurements a thick target was used, which was made by melting pieces of lithium metal on a brass plate in a vacuum. Much more satisfactory were thin evaporated lithium targets used at proton energies of 0.46 and 1.15 Mev. These thin targets were made in a high vacuum by evaporating lithium metal from a steel crucible onto the brass target backing. Both thin targets used had about the same thickness, 0.36 mg/cm^2, as determined by weighing. This corresponds to about 70 kev for protons of 1.15 Mev and to about 150 kev for protons of 0.46 Mev.

In order to monitor the total gamma-ray intensity from the cyclotron target, two Geiger counters were placed in lead shields about 60 cm away from the target, one above, and one below. Two monitors were used merely to obtain a check on the constancy of one of them.

E. Resolution

The various factors which may contribute to the resolution width of the spectrometer are the following:

(1) The Finite Width of the Counters

This is the most important contribution to the resolution width provided a sufficiently thin radiator is used to minimize multiple scattering of the electrons. Ideally, the effect of the counter width is to give a triangular resolution function. That is, the observed shape of a sharp gamma-ray line would be an isosceles triangle, with a base equal to the fraction $2w/2r$ of the energy of the line, where w is the width of the counters and $2r$ their separation. This counter separation is somewhat different for each of the seven output channels of the coincidence circuit, as described above. However, by using the average value $\langle 2r\rangle_{Av}=24$ cm, and the geometrical width of the counters, $w=0.80$ cm, we obtain for the percentage width of a line at half-maximum, due to the finite size of the counters alone, $w/\langle 2r\rangle_{Av}=3.3$ percent.

(2) Scattering of Electrons by the Counter Wall, or by the 0.005-in. Aluminum Window in Front of the Counters

Because of this scattering the edge of a counter is not sharply defined as far as the electrons are concerned. If an electron enters the $\frac{1}{32}$-inch wall separating two adjacent counters, for example, it will almost certainly be scattered into one or the other of the counters, and thus be recorded. Moreover, an electron may sometimes be scattered in such a direction as to pass through two or more counter walls, and thus be recorded simultaneously in two or more of the seven different energy channels of the spectrometer. We believe that this effect is responsible for the low, broad "tail" which appears at the base of the observed gamma-ray lines. If so, this tail should be approximately symmetrical on the high and low energy sides.

The effect of scattering in the 0.005-in. Al window is to spread the electrons which would enter the counter row at a given point over an area of width approximately 2δ. This increases the counter width by something of the order of δ,

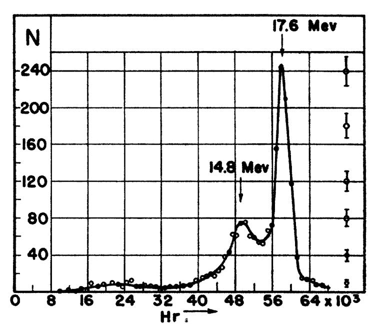

FIG. 3. Survey of the lithium gamma-ray spectrum between 3 and 19 Mev, obtained with a thick lithium target and protons of energy 1.15 Mev. The 0.002-in. Cu radiator was used in the spectrometer. The number of pair coincidences, N, obtained is plotted against Hr in gauss cm, where r is the *sum* of the radii of the two electrons of a pair. The standard statistical errors of each point, $(N)^{\frac{1}{2}}$, are indicated on the right of the curve.

Purcell, H. C. Torry, and R. V. Pound, Phys. Rev. **69**, 37 (1946); A. Roberts, Rev. Sci. Inst. **18**, 845 (1947).

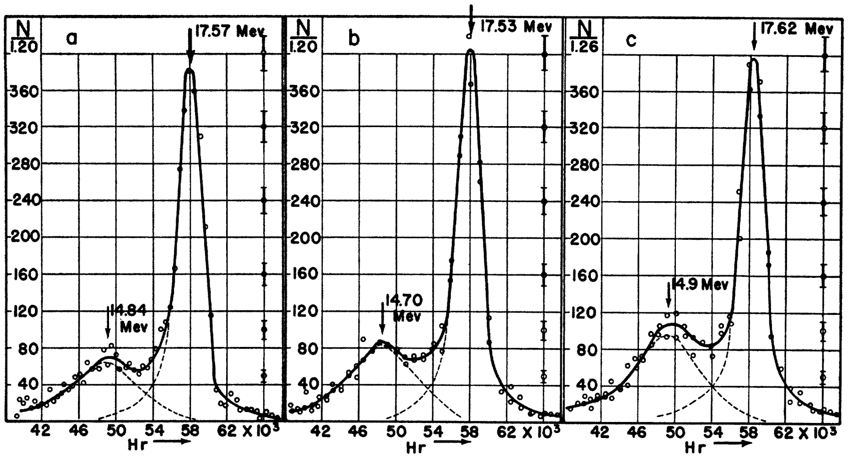

FIG. 4. Detail of the two gamma-ray lines from lithium bombarded with protons of three different energies: (a) Proton energy 0.46 Mev—target thickness approximately 150 kev; (b) proton energy 0.75 Mev—thick target; (c) proton energy 1.15 Mev—thick target. The 0.002-in. Cu radiator was used for all three curves.

in its effect on the resolution. Table I shows values of δ calculated for three different electron energies, from the distance between aluminum window and counters, and from the mean square angle of multiple scattering.[36]

$$\langle\Theta^2\rangle_{\text{Av}} = E_s^2 t/p^2\beta^2, \quad (11)$$

where $E_s = 21$ Mev, and t is the thickness in radiation lengths, of the material traversed by the electron.

(3) *Multiple Scattering of Electrons in the Radiator*

If either electron of a pair is scattered in any direction from the normal to the radiator, it will appear to have too low an energy, because of the properties of 180-degree focusing. The result is to make the observed gamma-ray line asymmetrical, with a tail on the low energy side. The magnitude of this effect may be obtained by calculating the average lowering of the measured gamma-ray energy, $\langle\Delta k/k\rangle_{\text{Av}}$. This may be easily found with the help of the formula (11), and the assumption that all angles involved in the calculation are small. The result is tabulated in Table II for the 17.6-Mev lithium gamma-ray, and the 6.1-Mev fluorine gamma-ray, for the radiators actually used.

(4) *Angular Divergence of the Electrons in the Pair Production Process*

This has, of course, the same effect as angular divergence caused by multiple scattering in the radiator.

The angular distribution of electrons in pair production is not known explicitly at small angles, but a characteristic angle of emission of an electron (or positron) of energy E is $\theta_p \approx \mu/E$. Except for very thin radiators, this is smaller than the multiple scattering. It imposes, however, a fundamental lower limit on the angular divergence, and means that it is useless to employ a radiator so thin that the mean square scattering angle $\langle\Theta^2\rangle_{\text{Av}}$ is reduced below $\theta_p^2 \approx \mu^2/E^2$. The two become equal for a radiator thickness $T = 0.0011$ radiation lengths. This corresponds, for example, to 0.004-in. aluminum, so the effect of the angular divergence in pair production must be comparable to the effect of multiple scattering when the 0.003-in. aluminum radiator is used. It will be noted that this is independent of the electron energy since the energy dependence of the two angles is the same.

(5) *Deviations from Normal Incidence upon the Radiator, of Gamma-Rays Striking the Radiator far from its Center*

The effect of the angular divergence arising from non-normal incidence of the gamma-rays on the radiator is small, and when calculated from the geometry of the apparatus, gives

$$\langle\Delta k/k\rangle_{\text{Av}} = 0.37 \text{ percent.}$$

(6) *Energy Loss of Electrons in the Radiator*

The angular divergence of electrons from the normal to the radiator tends to make the gamma-ray line asymmetrical rather than to shift the position of the peak. Loss of energy by the electrons in the radiator will, however, cause the peak to shift toward lower energy by just the amount of the average energy loss. The shifts in the observed gamma-ray lines resulting from energy loss by inelastic collisions have been found[36] to have the following small values:

$\Delta k = 0.072$ Mev for the 17.6-Mev lithium gamma-ray and the 0.002-in. Cu radiator. $\Delta k/k = 0.4$ percent.

$\Delta k = 0.032$ Mev for the 6.1-Mev fluorine gamma-ray, and the 0.003-in. Al radiator. $\Delta k/k = 0.5$ percent.

In addition to shifting the position of the gamma-ray lines by the above amount, energy loss in the radiator also produces a small loss of resolution. This arises from the fact that pair electrons traverse thicknesses of the radiator varying from zero up to the full thickness. The resulting loss of resolution is indicated by $\Delta k/k$ above.

The effect of energy loss by radiation is considerably smaller, even for the high energy lithium radiation, which can produce electrons of sufficient energy that the average radiation loss is comparable with the collision loss in copper, and greater than the collision loss in lead.[40] This is because radiation of quanta of all energies up to the primary energy of the electron makes an appreciable contribution to the average radiation loss, whereas only processes in which the electron retains above 80 or 90 percent of its energy can affect the shape of an observed gamma-ray line. Losses greater than this merely produce a small background of low energy pairs.

(7) Fluctuations in the Magnetic Field

Ripple in the magnetic field was measured to be less than 0.3 percent, and slow time variations were minimized by regulating the magnet current. The regulator used did not work perfectly, but the current was held constant to about 0.5 percent, or better.

(8) Secondary Radiation from the Lead Shielding

The effect of secondary radiation from the lead shielding is difficult to estimate, but qualitatively it would be expected to contribute a small background of low energy pairs more or less evenly distributed below the energy of the primary gamma-radiation.

A somewhat related question is whether any of the pairs which cause coincidence can have been produced at places other than in the radiator. To find this out, the counting rate was observed without a radiator in the spectrometer. The background thus observed was of the order of 1 to 3 percent, showing that nearly all pairs observed actually come from the radiator.

The combined effect on the resolution of all the

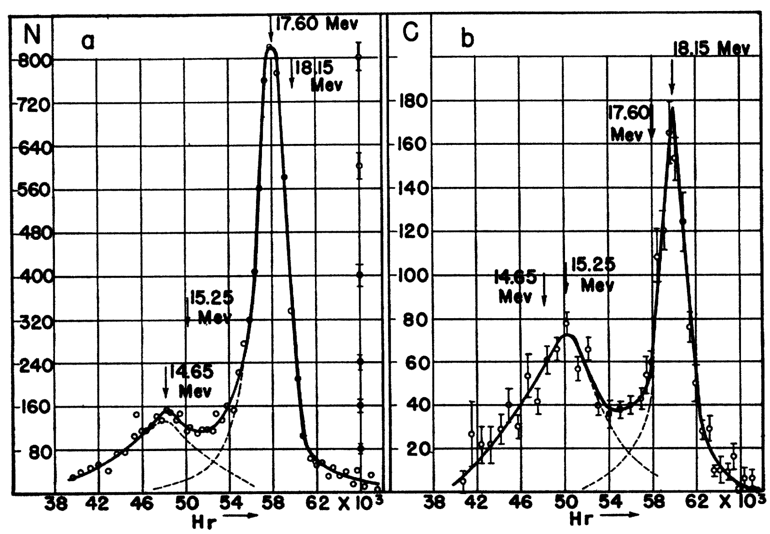

FIG. 5. Thin target lithium spectrum at two different proton energies, obtained with the 0.004-in. Cu radiator: (a) Proton energy 0.46 Mev—target thickness approximately 150 kev; (b) proton energy 1.15 Mev—target thickness approximately 70 kev. In curve (b) the relative coincidence rate C is plotted rather than the number of coincidences N obtained, since not all points were measured for the same number of monitor counts. A shift in energy of the two gamma-ray lines with increase in proton energy is apparent, as well as a marked increase in the relative intensity of the lower energy line with increasing proton energy.

[40] W. Heitler, *Quantum Theory of Radiation* (Oxford University Press, London, 1936).

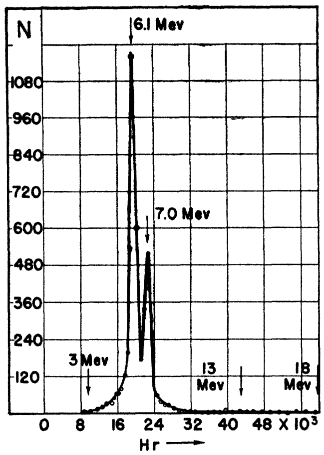

FIG. 6. Survey of the fluorine gamma-ray spectrum between 3 and 18 Mev obtained with a thick CaF_2 target, 1.15-Mev protons, and the 0.002-in. Cu radiator.

factors discussed above is best seen by looking at the measured gamma-ray lines in Figs. 4 and 7. It is probably safe to assume that the observed widths of the higher energy lithium line, and the 6.13-Mev fluorine line, for example, are entirely experimental. The widths of these lines at half-maximum are, respectively, 5.5 and 6.2 percent of the gamma-ray energy.

III. PROCEDURE

Each measurement of a spectrum was made by recording the number of coincidences occurring per fixed number of monitor counts, in each of the seven different energy channels of the spectrometer, at a sequence of values of the magnetic field. Successive values of the magnetic field were chosen in such a way as to simplify the plotting of the data. Frequently a set of points was repeated with the same energies represented by different channels, in order to make sure that all the channels were equivalent. The time required to make a complete spectrum measurement was from five to fifteen hours, with a proton current of 50–100 μa.

The proton energy was varied by changing the frequency of the cyclotron. The energies were determined from the cyclotron frequency and the rather uncertain radius of the last orbit, so they may be in error by ten percent.

IV. RESULTS AND CONCLUSIONS

Measurements of the spectra of gamma-radiation from lithium and fluorine under proton bombardment have been made under various conditions of proton energy, target thickness, and radiator thickness. The data are shown by the curves in Figs. 3–8, and a summary is given in Table III of the conditions under which each measurement was made.

The curves of Figs. 3–8 give the number of coincidences N observed, as a function of Hr, which is approximately proportional to the gamma-ray energy. (Eq. (10).) The energies of all gamma-ray lines, as indicated by the arrows in these figures, have been corrected for the small energy loss of the pair electrons in the radiator.

In obtaining the ratio of intensities of two lines from the areas under the corresponding peaks, corrections have been made for two effects which tend to suppress the low energy end of the curves as plotted in Figs. 3–8. The first of these is simply that the cross section for pair production, and thus the sensitivity of the spectrometer, increases with the gamma-ray energy.[40] The second is that the resolution width due to the finite size of the counters increases directly with the gamma-ray energy. (The percentage width remains constant as shown above in discussing the resolution.) The probability that an electron pair be counted in a given pair of counters is independent of the energy of the gamma-ray producing the pair, provided the magnetic field has the appropriate value given by (10). However, the magnetic field interval throughout which gamma-rays of a given energy can be recorded in the given pair of

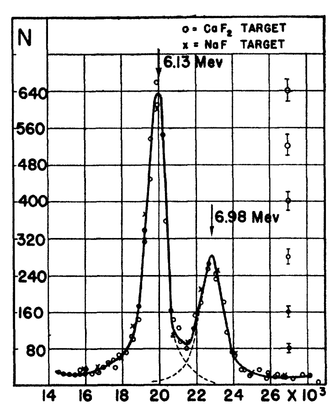

FIG. 7. Detail of the two fluorine lines observed with 1.15-Mev protons and the thin 0.003-in. Al radiator to obtain the best resolution. Data using thick targets of both CaF_2 and NaF are shown.

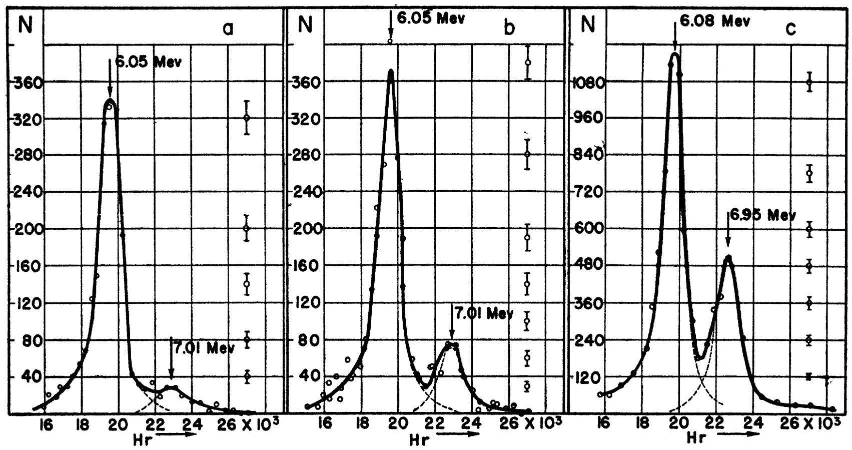

FIG. 8. The behavior of the two fluorine lines with change in proton energy. The 0.002-in. Cu radiator was used. (a) Proton energy 0.45 Mev—thick NaF target; (b) proton energy 0.70 Mev—thick NaF target; (c) proton energy 1.15 Mev—thick CaF_2 target. The relative intensity of the two lines changes with the proton energy. However, within the experimental accuracy, the energies of the two gamma-ray lines do not change.

counters is directly proportional to the magnetic field. Thus, for a gamma-ray line of given intensity, the area under the measured peak will be proportional to this resolution width, and thus to the gamma-ray energy.

A. Lithium

A survey of the spectrum between 3 and 19 Mev for a thick lithium target bombarded with 1.15-Mev protons is shown in Fig. 3. No new gamma-ray lines were found, but the line at 14.8 Mev previously reported[5] is clearly resolved from the 17.6-Mev line.

A detailed study of the two lithium lines for a thick target** at three proton energies, 0.46, 0.75, and 1.15 Mev, is shown in Fig. 4. It will be noticed that the lower energy line is considerably broader than the experimental resolution width. This could indicate the presence of two or more unresolved lines, but it finds a natural explanation in the nuclear transition (1) believed to be responsible for the 14.8-Mev gamma-ray.

$$Li^7+H^1 \rightarrow Be^{8*} \rightarrow Be^{8**}+h\nu. \quad (1)$$

The radiative transition giving the 14.8-Mev gamma-ray leaves the Be^8 nucleus in an excited level at 2.8 Mev, according to the difference in energy of the two gamma-ray lines. This energy agrees with that of a level in Be^8 which is known from other experiments[41, 42] to be broad because of its short lifetime against decay into two alpha-particles. From experimental data of Oliphant, Kempton, and Rutherford[41] on the energy distribution of alpha-particles produced in the reaction:

$$\begin{aligned} B^{11}+H^1 &\rightarrow Be^{8**}+He^4+Q_1, \\ Be^{8**} &\rightarrow 2He^4+Q_2, \end{aligned} \quad (12)$$

Bethe[43] obtains an approximate width of 0.8 Mev for the Be^8 level involved in this reaction, and an excitation energy of 2.8 Mev. One would like to identify this level with the one involved in reaction (1) above, and, further, with the lowest excited level of Be^8 obtained from the theoretical calculations of Feenberg and Wigner.[44] Theoretically, the first excited level of Be^8 is a ^1D level at about 2 Mev. The agreement between this energy and the experimental value 2.8 Mev is as good as could be expected from the rough approximations in the theory.

Although the 2.8-Mev levels of Be^8 involved in reactions (1) and (12) are probably the same, the agreement between the two experiments is not perfect. The width of the 14.8-Mev gamma-ray line appears to be considerably greater than 0.8 Mev, namely, of the order of 2.1 Mev. This is only a rough estimate, however, since it involves

** Although a thin evaporated Li target was used at proton energy 0.46 Mev a thick target can be expected to give the same result, since the yield of gamma-rays below the resonance energy of 0.440 Mev is very small.

[41] M. L. E. Oliphant, A. E. Kempton, and Lord Rutherford, Proc. Roy. Soc. **A150**, 241 (1935).

[42] J. D. Cockcroft and W. B. Lewis, Proc. Roy. Soc. **A154**, 246 (1936); P. I. Dee and C. W. Gilbert, Proc. Roy. Soc. **A154**, 279 (1936); C. L. Smith and E. B. M. Murrell, Proc. Camb. Phil. Soc. **35**, 298 (1939).

[43] H. A. Bethe, Rev. Mod. Phys. **9**, 217 (1937).

[44] E. Feenberg and E. Wigner, Phys. Rev. **51**, 95 (1937).

a somewhat arbitrary separation of the two lines shown by the broken curves of Figs. 4 and 5.

The three curves of Fig. 4 show a tendency for the relative intensity of the 14.8-Mev line to increase with increasing proton energy. Such a trend might be expected if the spectrum of radiation produced by protons at energies above the 440-kev resonance differs from that of the radiation from the resonance. Tangen (unpublished)*** and the Pasadena group[45] have reported that the radiation above the resonance is slightly less energetic, as determined from measurements of the absorption of secondary electrons.[46] To obtain further information on this point, and on the origin of the two gamma-ray lines, the data shown in Fig. 5 were taken. These two curves were obtained with thin targets at proton energies of 0.46 and 1.15 Mev. Thus the first curve shows essentially the gamma-ray spectrum produced by protons of the resonance energy, 440 kev, while the second curve shows the spectrum arising from that part of the gamma-ray excitation curve[13, 14] considerably above the 440-kev resonance. It is immediately evident that the relative intensity of the lower energy line is considerably greater for 1.15-Mev protons than for 0.46-Mev protons, but it is also evident that both lines occur at both proton energies.

The ratio of intensities of the lower energy line to the higher energy line is found to be approximately 0.50 for 0.46-Mev protons; and 1.5 for 1.15-Mev protons.

Another interesting result may be seen by comparing the two curves of Fig. 5. This is a shift in the energy of the two peaks by just about the amount to be expected from the difference in energy of the protons: i.e., by $\frac{7}{8}$ the difference in proton energy.

The sharp, high energy line is produced by reaction (1) leaving the Be^8 nucleus in its ground level. The quantum energy of the gamma-ray will then be $h\nu = Q + \frac{7}{8}E_p$, where Q is the energy available from the mass change, and E_p is the proton energy. From the positions of the higher energy lines in Fig. 5, we obtain the value $Q = 17.2 \pm 0.2$ Mev, in agreement with the value 17.21 ± 0.08 obtained from the mass values.[47]

The best values for the energies of the two gamma-ray lines arising from the 440-kev lithium resonance are obtained from Figs. 4 and 5a: 14.8 ± 0.3 Mev, and 17.6 ± 0.2 Mev.

B. Fluorine

A general survey of the gamma-ray spectrum from a thick CaF_2 target bombarded with 1.15-Mev protons is shown in Fig. 6. The gamma-radiation previously believed to consist of a single line near 6.3 Mev, is clearly resolved into two lines at 6.1 and 7.0 Mev. (Several lines between 5.4 and 7.2 Mev have been reported for high energy protons, 5 Mev, by Phillips and Kruger.[48]) No lines between 8 and 18 Mev exist having an intensity greater than one percent of the 6.1-Mev line. In particular, no radiation is observed near 13 Mev with an intensity greater than about 0.3 percent of that at the 6.1-Mev line, confirming the result of Delsasso, Fowler, and Lauritsen.[6] This is the energy to be expected for a gamma-ray arising from reaction (4).

A detailed investigation of the two fluorine lines is shown in Fig. 7, for a proton energy of 1.15 Mev, and thick fluoride targets. Both CaF_2 and NaF targets were used in order to confirm previous results[11] that the fluorine and not calcium is responsible for the radiation. Because of the use of thick targets, all resonances below 1.15 Mev in the gamma-ray excitation curve[14, 29, 30] contribute to the intensity of the lines. However, the resonances at proton energies 862 and 927 kev are much stronger than the others, and probably contribute a major fraction of the intensity. An extremely thin radiator of 0.003-in. aluminum was used in obtaining the data of Fig. 7, in order to achieve the best possible resolution. From the positions of the two peaks, we obtain for the quantum energies of the two fluorine gamma-rays: 6.13 ± 0.06 Mev, and 6.98 ± 0.07 Mev.

Using a somewhat thicker radiator of 0.002-in. Cu, the behavior of the thick target spectrum with changes in the bombarding proton energy

*** *Note added in proof:* Tangen's work is published: Roald Tangen, Kgl. Norske Vid. Sels. Skrifter (1946) NR1.

[45] W. F. Hornyak and T. Lauritsen, Rev. Mod. Phys. **20**, 191 (1948).

[46] W. A. Fowler, C. C. Lauritsen, and T. Lauritsen, Rev. Mod. Phys. **20**, 236 (1948).

[47] H. A. Bethe, *Elementary Nuclear Theory* (John Wiley and Sons, Inc., New York, 1947).

[48] J. A. Phillips and P. G. Kruger, Phys. Rev. **72**, 164 (1947).

was investigated. Measurements at proton energies of 0.45, 0.70, and 1.15 Mev are shown in the three curves of Fig. 8. A marked decrease in the relative intensity of the 7.0-Mev gamma-ray is noticed as the proton energy decreases. At 0.45-Mev proton energy this line has almost disappeared, and the radiation is nearly monochromatic. At this proton energy the resonance at 334 kev alone should contribute to the gamma-ray intensity. However, the proton energy is not very well known, so it is not impossible that the next fluorine resonance, at 479 kev, may have contributed something to the gamma-ray intensity in Fig. 8a.

From the data shown in Fig. 8, the ratio R of intensities of the 6.1- to the 7.0-Mev lines has been calculated for the three different proton energies.

Proton energy, E_p	Ratio of intensities, $R=I(6.1)/I(7.0)$
0.45 Mev	23
0.70	5.8
1.15	2.6

The three curves of Fig. 8 show that the energies of the two gamma-ray lines do not change with the bombarding proton energy, within the experimental accuracy. This is analogous to the results obtained by Dee, Curran, and Strothers,[7] and by Lauritsen, Lauritsen, and Fowler,[23] and used by them as an argument against reaction (5), and also against the emission of two successive quanta by the excited Ne^{20} nucleus. However, the present result is more conclusive since the earlier experiments failed even to resolve the two gamma-ray lines.

The results of the present experiment thus substantiate the belief that reaction (3) is responsible for the origin of the fluorine gamma-rays.

$$F^{19}+H^1\rightarrow Ne^{20*}\rightarrow O^{16*}+He^4+Q,\quad O^{16*}\rightarrow O^{16}+h\nu. \tag{3}$$

It is necessary, however, to assume two oxygen gamma-ray levels, O^{16*} and O^{16**}, in order to account for the two gamma-rays, and two corresponding values of Q, Q_1, and Q_2. This means that there are at least three rather close lying levels of O^{16} at 6–7 Mev. These are the "pair level" ($J=0$) of the reaction (7), at 6.0 ± 0.2 Mev, and the two "gamma-ray levels" at 6.1 and 7.0 Mev.***

The value $Q=1.81\pm0.04$ Mev for reaction (3) obtained by Becker, Fowler, and Lauritsen[27] corresponds to the lower energy gamma-ray, 6.13 Mev. Calling this Q_1, we obtain $Q_2=0.96\pm0.08$ Mev. (The alpha-particles preceding emission of the 6.98-Mev gamma-ray line may explain the small low energy alpha-particle peaks appearing in Figs. 5 and 6 of their paper.)

The sum of the gamma-ray energy 6.13 Mev and $Q_1=1.81$ Mev is 7.94 ± 0.08 Mev. This is to be compared with the energy available from the mass change,[47] 8.12 ± 0.24 Mev, and with the value $Q=7.95$ Mev obtained for the long-range alpha-particle reaction (6) by Burcham and Smith.[22]

The low energy of the alpha-particles preceding emission of the gamma-rays suggests that the observed decrease in relative intensity of the higher energy gamma-ray line with decrease in proton energy may be explained by the effect of the potential barrier on the relative probability of emission of the two alpha-particles. The higher energy gamma-ray follows the lower energy alpha-particle, which is suppressed more rapidly by the potential barrier as the proton energy decreases.

ACKNOWLEDGMENTS

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*** For a detailed discussion of the known energy levels in O^{16}, Be^8, and other light nuclei, see the review article by Hornyak and Lauritsen, reference (45).