Gamma-Rays from Fluorine Due to Proton Bombardment

E. J. BERNET, R. G. HERB, D. B. PARKINSON
Department of Physics, University of Wisconsin, Madison, Wisconsin

(Received July 19, 1938)

A detailed study has been made of the resonance excitation of gamma-rays from fluorine when bombarded with high speed protons in the energy range 0.18 Mev to 2.2 Mev. Because of improvements in the high voltage generator and in the preparation of uniform thin fluorine films, the resonance peaks obtained are much narrower than in the previous work at this laboratory, and many new resonances have been discovered. For the seven resonance peaks which are best defined, estimates are given as to voltage position and half-width.

INTRODUCTION

GAMMA–RADIATION from the disintegration of fluorine by protons was first observed by McMillan[1,2] in 1934. By the use of a cyclotron to accelerate protons, and a thick calcium fluoride target, he obtained a smoothly increasing excitation curve up to his maximum voltage of 1.15 Mev. However, the work of Hafstad and Tuve[3] and of Hafstad, Heydenburg and Tuve,[4] who used an electrostatic generator and a thick target of calcium fluoride, showed that the gamma-ray excitation curve from fluorine was not a smooth exponential increase but consisted of a number of well-defined steps in the voltage region from 100 kv to 1000 kv. Their work showed the advantages of a monochromatic beam of protons as well as steady and accurately measured generator voltages for obtaining excitation curves. The work by Herb, Kerst and McKibben[5] in 1937 was in good agreement with that of Hafstad, Heydenburg and Tuve in the lower voltage range and carried the data up to slightly over 2 Mev. Since this first work was only of an exploratory nature it seemed desirable to repeat experiments on excitation of gamma-rays from fluorine in an effort to determine widths and positions of resonances more accurately.

APPARATUS

The Wisconsin electrostatic generator operating under 100 pounds air pressure has been described in a paper by Herb, Parkinson, and Kerst.[6] Recent improvements and present technique are described in a paper by Parkinson *et al.*[7] It is now possible to keep the generator voltage constant to within approximately $\frac{1}{4}$ percent over most of the time required for a measurement, with occasional fluctuations of the order of $\frac{1}{2}$ percent.

Figure 1 shows the arrangement of the target chamber and electroscope used in this work. High speed protons entering from the left pass through a defining aperture $\frac{3}{16}''$ in diameter. A thin platinum sheet was placed over the outside of the defining aperture to cut down gamma-radiation produced by protons stopped around the edge. The main chamber, containing the target, is insulated by a clear Bakelite plug and is used as a Faraday cage to measure the proton current incident on the target. The disk containing the defining aperture is grounded and the target chamber is kept at a negative potential of about 45 volts so as to prevent electrons generated at the edge of the hole from entering the chamber. Since the proton current is rather unsteady, a current integrator, which has been previously described,[5] is used to measure total charge. A recalibration of the current integrating arrangement in terms of a standard cell was made for the present work and a small correction for leakage of the input circuit as a function of time has been applied to all the data.

A Lauritsen type electroscope was used for measurement of relative gamma-ray intensities. The electroscope was tested for linearity and

[1] McMillan, Phys. Rev. **46**, 325 (1934).
[2] McMillan, Phys. Rev. **46**, 868 (1934).
[3] Hafstad and Tuve, Phys. Rev. **48**, 306 (1935).
[4] Hafstad, Heydenburg and Tuve, Phys. Rev. **50**, 504 (1936).
[5] Herb, Kerst and McKibben, Phys. Rev. **50**, 691 (1937).
[6] Herb, Parkinson and Kerst, Phys. Rev. **51**, 75 (1937).
[7] Parkinson, Herb, Bernet and McKibben, Phys. Rev. **53**, 642 (1938).

readings were always taken over the same scale divisions. It was found necessary to use lead shielding, arranged as shown in Fig. 1, to cut down background ionization by gamma-rays produced at the defining aperture and by x-radiation from the generator. The natural leak of the electroscope was found to be about 0.020 divisions per minute, and this correction has been applied uniformly to all the data.

Target Preparation

In our previous work on gamma-radiation from fluorine, thin targets were prepared by electrolyzing a piece of sheet nickel in hydrofluoric acid. As nickel fluoride is not soluble in hydrofluoric acid, the film thickness could be governed by the current and by the length of time in electrolysis. Nickel, however, was found to give considerable gamma-radiation when bombarded by protons with energies above 1 Mev and it is therefore not satisfactory as a base for a thin fluorine target. Because of this difficulty with thin targets on nickel, the use of thick targets was considered, and some work was done with thick calcium fluoride crystals. It was found, however, that a detailed analysis of a complex excitation curve is difficult to obtain with a thick target. Resonances are indicated by steps in a thick target yield curve, which in the low voltage region can be determined with fair accuracy, but a weak resonance at high voltage can easily be missed, since it appears only as a relatively small increase in an intensity which is already high. When a thin target is used, resonances appear as peaks in the yield curve, and because of the large change of relative intensity in the resonance region, more accurate measurements are possible.

The considerations outlined above showed that for a suitable target a uniform thin film of some fluorine compound must be prepared on a metal base which gives a low yield of gamma-radiation.

Platinum was found to give a very low yield of gamma-radiation (probably none) when bombarded with 2 Mev protons, but attempts to form a film of a fluorine compound on a platinum surface were not successful. A lead sheet was next examined for gamma-ray yield. A measureable intensity was observed at high voltage, but it was sufficiently low to be negligible in comparison to the fluorine yield, and it is probable that the yield observed was due to contamination. Thin films of lead fluoride were easily formed on a lead sheet by dipping the sheet into hydrofluoric acid. However, all yield curves obtained from these targets gave broad resonance peaks, and the yield at a given voltage decreased quite rapidly with time. It is quite likely that because of heat developed during bombardment, the lead fluoride film diffuses into the lead base. Pure tantalum obtained from the Fansteel Corporation was then tried as a target base, and since it was found to be very satisfactory, it was used for all the data presented in this paper.

In the preparation of a thin film on a tantalum sheet, the surface of the tantalum was first polished with very fine emery paper and was then cleaned by boiling in water and by washing in alcohol. The tantalum was next electrolyzed in concentrated hydrofluoric acid at currents of from 50 to 250 milliamperes for approximately one minute. The tantalum fluoride formed is dissolved by the hydrofluoric acid, but the electrolyzing process appeared to be necessary for additional cleansing of the metal surface. Upon removing the target from the hydrofluoric acid, a few drops of the solution were left on the surface. When these droplets dried, the tantalum fluoride gathered together in lumps and resonance peaks were observed to be broad even from a film giving very low intensity.

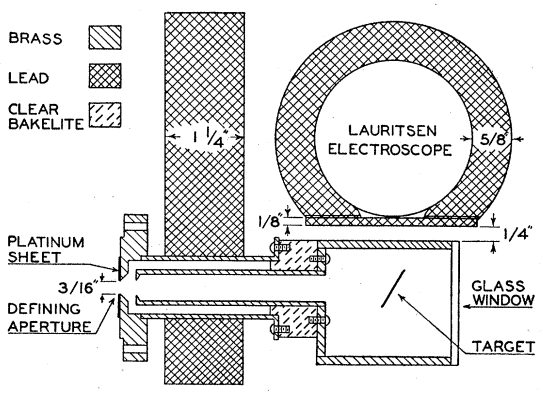

FIG. 1. Target chamber and electroscope.

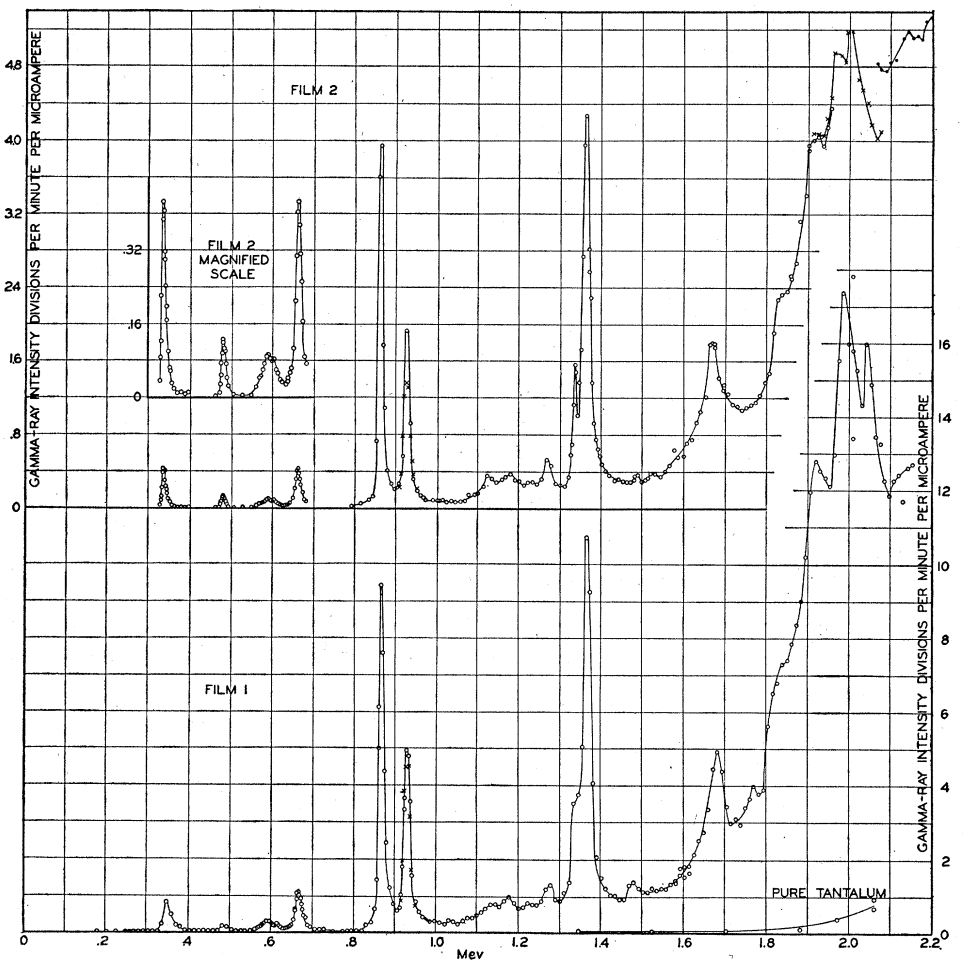

FIG. 2. Gamma-ray intensity *vs.* energy of bombarding ions.

The present technique consists of removing the target from the solution and allowing a few drops to remain on the surface just as before, but then these drops are spread out over the surface of the target by adding a few drops of alcohol which wets the surface of the tantalum uniformly. The mixture is flowed back and forth over the surface by tilting and then drained off and the target allowed to dry. With experience it is possible to control the thickness of the resulting film to some extent, but before films were used for yield curves, they were first tested for yield and uniformity by going over the two resonances at 0.862 Mev and 0.927 Mev and noting the height of peaks and more especially the extent of the drop between peaks.

RESULTS

Figure 2 shows the excitation curves obtained from two different tantalum fluoride films. A background run on a clean tantalum sheet without a fluorine film (Fig. 2) gave a very low yield, and it is probable that the intensity observed was entirely due to x-radiation from the generator.

FILM 1

The run on film 1 (Fig. 2) was begun at 0.8 Mev and carried up to 2.15 Mev. The same spot on the film was used for all the data. The doublet peaks at 0.862 Mev and 0.927 Mev which were not resolved in the previous work at this laboratory were very well resolved in this

run. One point on the prominent peak at 1.36 Mev appears to be off, but this was later shown to be due to a satellite. Although the peak at 1.67 Mev is very broad, it has never given any indication of being a doublet in subsequent work. Above 1.8 Mev the form of the yield curve indicates that in this region there are a number of intense levels too closely spaced for good resolution.

To determine the condition of the film spot after this energy range had been covered, a check run was taken on the resonance peak at 0.927 Mev (film 1, crosses). The peak appeared at the same voltage as in the previous work and yields were practically unchanged. This is a very satisfactory check both on the dependability of the generating voltmeter and on the stability of the fluorine film.

The gamma-ray intensity was next investigated below 0.8 Mev by bombardment of the same spot on film 1. In previous work at Washington, D. C.[4] and at this laboratory,[5] a very broad resonance was indicated in the region between 0.5 Mev and 0.7 Mev, and a sharp resonance was found at 0.330 Mev. The data from film 1 show sharp resonances at 0.660 Mev, 0.479 Mev, and 0.334 Mev, and a broad resonance with its peak at about 0.589 Mev. A good curve was easily obtained for the resonance at 0.660 Mev, but a great deal of time was spent on the 0.589 Mev resonance, since several yield curves indicated the possible presence of a closely spaced doublet. The resonances at 0.334 Mev and 0.479 Mev were not examined in great detail with film 1 since prolonged bombardment in the region of 0.6 Mev had damaged the film and resonances were somewhat broadened. The data in the lower voltage range were obtained by use of diatomic ions and with 50 pounds air pressure in the generator tank.

Film 2

To obtain information regarding the influence of film thickness on the half-width of the resonances obtained with film 1, another film (film 2) was prepared. At the 1.36 Mev resonance this film gave an intensity only 0.4 as high as the intensity from film 1. As with the previous film, only a single spot on film 2 was used for the complete curve. After the complete voltage range had been covered, a check run was taken on the 0.927 Mev peak to determine the condition of the film (film 2, crosses). Although the resonance peak obtained in the check run is lower in intensity than the original run, the values of the voltage position and half-width agree very well. The region below 0.5 Mev was taken in more detail with this film than with film 1, and the first four resonance peaks in the low voltage range are shown with the ordinate scale increased by a factor of five.

Additional runs were taken with film 2 on the peak at 0.589 Mev, but no better resolution was obtained than with film 1. Every yield curve obtained for this peak has indicated the presence of a close doublet, but definite resolution has not been obtained. The satellite on the low voltage side of the peak at 1.363 Mev was first resolved with film 2. Two subsequent runs on this peak with different films are shown in Fig. 3A and Fig. 3B. By a change in ordinate scale these peaks were brought to the same height for comparison of the position of the satellite. Two separate high voltage runs were taken on film 2, one from 1.9 Mev to 2.1 Mev (crosses),

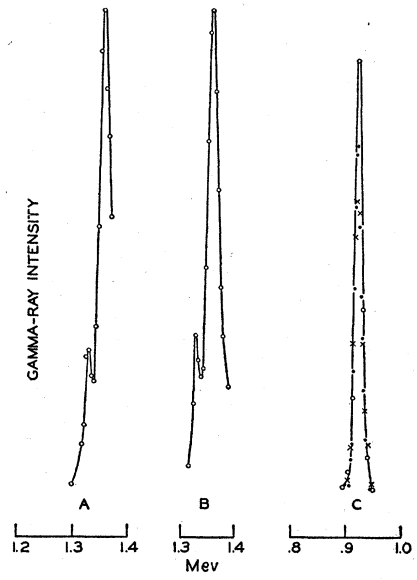

FIG. 3. (A) (B) Check runs on peak at 1.363 Mev to observe satellite. (C) Readings taken to check voltmeter. Resonance peak in fluorine, open circles are original run on film 2, crosses are the check run with protons, solid circles are the check run with diatomic ions.

and the other, taken a day later, from 2.1 Mev to 2.2 Mev (solid circles) (Fig. 2). The rise in the intensity at 2.1 Mev between the two runs is difficult to understand since it indicates that the film was thicker for the higher voltage run, which was taken last. A possible explanation can be made if it is assumed that the fluorine compound formed in preparing the target is TaF_5. This compound is a liquid above 97°C, and if the temperature of the target should rise sufficiently at some time during bombardment, there might be a rearrangement of the film.

Above 1.7 Mev the data from film 2 do not agree well with film 1 data. In general form the curves are similar, but the relative heights of peaks and the extent of drop between peaks is not consistent. The radiation in this voltage region is probably due to a number of prominent overlapping resonance levels. Thus to fix the position of a peak it is necessary to determine a rather small change in the intensity. Experimental inaccuracy due to nonuniformity of films, voltage fluctuations, and errors in electroscope readings probably account for the lack of consistency in the data.

Resonance Energies

In the energy region below 1.7 Mev ten resonance levels are quite well established. Their energy positions in Mev of bombarding protons are as follows: 0.334, 0.479, 0.589, 0.660, 0.862, 0.927, 1.26, 1.335, 1.363 and 1.67. As the levels above 1.7 Mev are not well resolved, no attempt has been made to estimate their energy positions. For the energy region from 1.0 Mev to 1.3 Mev only one resonance (1.26 Mev) is included in the list, although two more are indicated between 1.1 Mev and 1.2 Mev. The radiation in this region seems to be due to a number of weak overlapping levels. Another weak resonance is probably present at about 1.48 Mev.

Before the data on film 1 were taken, a calibration of the generating voltmeter was made at the 0.440 Mev resonance of lithium with both protons and diatomic ions (the value of 0.440 Mev for the lithium resonance was assumed as a standard for the voltage scale in this work). The data of film 1 are plotted with that calibration. Most of the data on film 2 were taken about five weeks later than the data on film 1, and the resonance peaks appeared to come at higher voltages. After the data on film 2 were complete the voltmeter was again calibrated with the 0.440 Mev resonance of lithium, and its sensitivity was found to be 1.6 percent higher than in the previous calibration. With the new voltmeter sensitivity, the voltage position of resonances of film 2 agreed with those from film 1 as closely as could be determined from the experimental curves. For the well-defined peaks, the voltage positions checked to within about 0.2 percent.

The increase in sensitivity of the voltmeter was very disturbing since it could not be explained at that time, and it indicated that the voltmeter might not be dependable unless calibrated frequently. A recent experience with another generator equipped with a similar voltmeter suggested an explanation which is probably correct. The voltmeter is mounted with the outer surface of its rotating vane approximately flush with the inner surface of the tank, and it was found that if the vanes were moved inward or outward by a small amount, the voltmeter sensitivity changed considerably. The voltmeter is supported on a flanged fitting and seats against a rubber gasket. The position of the vanes therefore depends on how much the gasket is compressed when the voltmeter is bolted to its supporting flange. When the voltmeter was taken off for oiling and remounted it is quite likely that the gasket was compressed more than before and that this change caused the observed increase in sensitivity. By a slight change in the method of mounting the voltmeter it will be possible to fix the position of the vanes much more accurately, and this source of trouble will be removed.

The linearity of the voltmeter was tested a number of times in the last two years, but as an additional check the 0.927 Mev resonance of fluorine was studied with diatomic ions for bombardment. These data together with the original data and the check run with protons are shown in Fig. 3C. The open circles are from the original run on this resonance with film 2, the crosses show the data of the check run with protons, and the solid circles are the data obtained with diatomic ions. Agreement is very

good, and it is believed that the greatest uncertainty in the voltage positions of the fluorine resonances is due to the uncertainty in the position of the lithium resonance which was assumed to be at 0.440 Mev.

Resonance Energies from CaF_2 Crystals

Several yield curves have been obtained in the region between 0.8 Mev and 1.0 Mev with thick CaF_2 crystals as targets. In the first runs with these targets the 0.862 Mev and 0.927 Mev resonances appeared at higher voltages. This shift was found to be caused by accumulation of charge on the crystals. The smallest crystal used (about 1 cm square and 1 mm thick) gave a shift of about 10 kev. Larger crystals caused a greater shift. To prevent the crystals from charging up, a fine tungsten wire was spot welded to the grounded target support and was bent so that its end pressed firmly onto the crystal at approximately the center of the region where the proton beam hit. With this arrangement the resonance voltages agreed with those determined from the thin films on tantalum. It is probable that the crystal becomes conducting over the area being bombarded, and that charge easily leaks off to a lead touching this area.

A second method of preventing accumulation of charge was also tried, and was found to be satisfactory. Fine mesh gauze (about 100 mesh) was etched with acid until it gave a transmission of over $\frac{1}{2}$. This was stretched over the crystal and was spot welded to the grounded target support. The gauze probably made contact with the crystal at only two or three places, and in some cases probably did not make contact where the proton beam hit. It is probable however that contact was not essential since protons hitting the gauze generate secondary electrons and this source of electrons should be sufficient to neutralize any charge on the crystal. All crystals with which this method was tried gave fairly consistent results.

Table I. *Half-widths of resonance peaks.*

Resonance Voltage Mev	Experimental Half-width kev		Corrected Half-width kev	
	Film 1	Film 2	Film 1	Film 2
0.334		9.8		8.0
0.479		12.1		10.5
0.660		15.7		14.4
0.862	13.4	12.1	9.8	10.9
0.927	18.8	15.7	15.5	14.6
1.335		9.2		8.3
1.363	23.3	20.6	20.8	19.8

Widths of Resonance Levels

The well-defined resonance peaks were plotted carefully to a large scale and their half-widths were determined. Table I gives these values in the columns showing experimental half-widths. Factors tending to increase the values of the observed widths over the true widths of the nuclear levels are (1) film thickness, (2) inhomogeneity of the proton beam, (3) voltage fluctuations.

If it is assumed that the thin films consist of TaF_5, film thickness can be determined by utilizing thick target yields. If a film is thin compared to the width of the nuclear resonance level, the area under a resonance peak is given by

$$A = IN' \int\int g(E-E')f(E_0-E')dEdE', \quad (1)$$

where

E_0 = resonance voltage,
I = proton current,
N' = number of fluorine atoms per cm^2,
E = generator voltage,
E' = voltage or energy of incident protons,

$g(E-E')$ gives the energy distribution of incident protons when the generator-voltage is held as close as possible to E. [The ratio of the number of incident protons with energy between E' and $E'+dE'$ to the total number of protons is equal to $g(E-E')dE'$.] The disintegration cross section for protons of energy E' is equal to $f(E_0-E')$. Since $\int g(E-E')dE = \int g(E-E')dE' = 1$ we have $A = IN' \int f(E_0-E')dE'$.

Therefore the area is independent of the homogeneity of the proton beam or voltage fluctuations providing they do not change while measurements are being made on a particular resonance peak.

The total contribution of a resonance level to a thick target yield curve (height of step) is given by

$$Y = IN \int\int g\{(E-ax)-E'\}f(E_0-E')dE'dx, \quad (2)$$

where x measures distance into the target,

a = stopping power of target material,
N = number of fluorine atoms per cm^3,
E' = the energy of protons at distance x in the target,
E, I, E_0, g, and f have the same meaning as in (1).

Since

$$\int g\{(E-ax)-E'\}d(ax)=1,$$

we have $$Y=\frac{IN}{a}\int f(E_0-E')dE'$$

and $$\frac{A}{Y}=\frac{N'}{N}a.$$

Thus the area under a thin target resonance peak divided by the height of the resonance step from a thick target curve gives the absorption thickness of the thin film regardless of the homogeneity of the proton beam.

From a yield curve taken with a CaF_2 crystal as a target the 0.862 Mev and 0.927 Mev resonances were found to contribute, respectively, 49 divisions per minute per microampere and 24 divisions per minute per microampere. Yields from CaF_2 were converted to yields from TaF_5 under the approximate rule that atomic stopping power varies with the square root of atomic weight. Thus yields from a thick target of TaF_5 should be 1.07 times as great as yields from CaF_2.

Areas under the 0.862 Mev and 0.927 Mev resonance peaks were determined for both film 1 and film 2, and the values found for film thicknesses are as follows: For film 1, with the 0.862 Mev resonance, the absorption thickness was found to be 3.59 kev and from the 0.927 resonance an absorption thickness of 4.01 kev was determined. For film 2, the two values were 1.21 kev from the 0.862 Mev resonance and 1.39 kev from the 0.927 Mev resonance.

The absorption thickness of a film should decrease with increasing voltage, yet the values determined are greater at the higher voltage resonance. This discrepancy is probably due to an inaccurate determination of the relative contribution of the two resonance levels to the thick target yield. The values of film thickness determined from the 0.862 Mev level are probably more accurate than those from the weaker 0.927 Mev level. Thus in correcting the experimental half-widths for film thickness, the values were assumed to be 3.6 kev for the absorption thickness of film 1 at 0.862 Mev and 1.2 kev for film 2 at 0.862 Mev. These values probably set a fairly accurate lower limit to film thickness. If other compounds of fluorine, such as lower fluorides of tantalum, were present in the films, absorption would be increased. Nonuniformity of the films or diffusion of the fluorine compound into the tantalum would also increase the absorption thickness of the films. In computing the absorption thickness of the films at other resonances, stopping power was assumed to vary inversely as the square root of the voltage. Experimental half-widths of the resonances, corrected for absorption thickness of the film, are given in Table I under the heading "corrected half-widths."

If thick target yield curves are used to determine resonance widths, the effect of film thickness does not enter. As several yield curves had been taken on CaF_2 crystals at the 0.862 Mev resonance and the 0.927 Mev resonance, they were examined for resonance widths. Following a suggestion by Professor Breit, we used expressions of the form

$$Y=A\left\{\tan^{-1}\frac{E-E_0}{\Delta E}+\frac{\pi}{2}\right\},$$

where ΔE is resonance half-width, for fitting the yield curves. These expressions did not fit the curves very well, but since they set reasonably close limits to the half-widths, better formulae were not developed. As closely as could be determined, the thick target resonance widths agreed with the thin film determinations.

The effect of voltage fluctuations and inhomogeneity of the proton beam on observed resonance widths is difficult to estimate, but the excellent resolution of the satellite at 1.33 Mev indicates that these factors are not giving large contributions to the widths of the broader levels.

An attempt was made to fit the thin target resonance peaks with dispersion terms of the form

$$Y=\frac{A}{(E-E_0)^2+(\Delta E)^2}.$$

The levels at 0.862 Mev and 0.927 Mev could be fitted fairly well, but a sum of two such expressions could not be made to fit the 1.363 Mev level and its satellite. Finally, to obtain an estimate of the half-width of the satellite, a dispersion formula was chosen to fit the intense 1.363 Mev level in the region above the satellite. This curve was subtracted from the experimental curve and a remainder was obtained which was assumed to be due to the satellite. The half-width determined for the satellite (9.2 kev) did not depend critically upon the form of the curve chosen for the main resonance peak.

Discussion of the Fluorine-Proton Reaction

The nature of the nuclear reaction responsible for the gamma-radiation from fluorine is as yet poorly understood. Several investigations have been made of the energy of gamma-rays from fluorine excited by protons at fairly low voltages. McMillan bombarded fluorine with 1.15 Mev protons, and from absorption measurements concluded that the radiation is monochromatic with an energy of 5.4 Mev. Delsasso, Fowler, and Lauritsen[8] recently measured the energy of the fluorine gamma-radiation with a cloud chamber and concluded that the radiation is monochromatic with an energy of 6.0 Mev. They used 0.750 Mev protons and were therefore obtaining radiation from the first four resonance levels. Gaerttner and Crane[9] made a recent study of the fluorine gamma-radiation with a cloud chamber, and they obtained two gamma-ray lines—at 4.0 Mev and 5.7 Mev. They used 0.40 Mev protons in their first work, but then repeated the measurements with 0.75 Mev protons, and obtained the same gamma-ray lines. These results indicate that there is no difference in the character of the radiation from the first four resonances of fluorine. Practically nothing is known, however, regarding the energy of radiation from the high voltage resonances.

Henderson, Livingston, and Lawrence[10] obtained alpha-particles with a range of 6 cm from fluorine bombarded by 0.675 Mev protons. This range corresponds to an energy of 7.08 Mev. The alpha-particles were observed, at a right angle from the proton beam, and when a correction is applied for the energy of the incident protons, a good energy balance is obtained with the reaction $F^{19}+H^1\rightarrow O^{16}+He^4$. It therefore appears that there can be no gamma-radiation accompanying the 6.0 cm alpha-particles. If the gamma-radiation is due to the reaction giving $O^{16}+He^4$, short range alpha-particles should be emitted. Although no short range alpha-particles have been observed, it is possible that they have been missed.

Another possible reaction, $F^{19}+H^1\rightarrow Ne^{20}$, is exothermic by 12.9 Mev exclusive of the energy due to the incident protons. The emission of two successive gamma-rays may be assumed, but with either the results of Delsasso, Fowler, and Lauritsen, or the results of Gaerttner and Crane, the energy balance is not good.

Discussions of the probable reaction responsible for gamma-ray emission from fluorine are given in the papers by Fowler and Lauritsen,[8] and by Gaerttner and Crane.[9]

Tentative Interpretation of Results*

The sharpness of the resonance levels observed in these experiments is surprising at first sight and indicates that there are selection rules which separate the energy levels of the Ne^{20} nucleus into at least two almost mutually isolated systems. Qualitatively the existence of a selection rule can be inferred from the failure of the Ne^{20} compound nucleus to disintegrate into O^{16} and He^4 in normal states. There is available for this at least 8.2 Mev which is more than sufficient to overcome the effect of the Coulomb barrier. In the absence of selection rules the mean life of a virtual Ne^{20} level would be expected to be short and the width of the levels would be expected to be comparable with that of the excited state of Be^8 which according to Dee and Gilbert is ~ 1 Mev. According to the indeterminacy relation this corresponds in order of magnitude to the time necessary for a particle with velocity $c/30$ to traverse a distance 6×10^{-13} cm. The width of the levels according to observation is

[8] Delsasso, Fowler and Lauritsen, Phys. Rev. **51**, 527 (1937).
[9] Gaerttner and Crane, Phys. Rev. **52**, 582 (1937).
[10] Henderson, Livingston and Lawrence, Phys. Rev. **46**, 38 (1934).

* This discussion is due to Professor G. Breit.

$\sim$10 kev and it may be less for some of the levels. It is necessary to explain the sharpening of the levels by a factor of at least 100 in comparison with the width expected on the one-body picture.

The necessity for reducing the probability of decay into O^{16} and He^4 in normal states exists independently of the actual process of γ-ray emission. It is immaterial for the present whether the γ-rays are emitted by an excited O^{16} nucleus or by cascade transitions in the Ne^{20}. The general situation is similar to that discussed by Oppenheimer and Serber for the bombardment of B^{11} with H^1.

It has been pointed out by Bethe[11] that the even parity and zero spin of O^{16} and He^4 offer a particularly simple possibility for ruling out the disintegration into normal O^{16} and He^4. The levels of Ne^{20} that have odd total angular momentum and even parity or even total angular momentum and odd parity are completely unable to dissociate into $O^{16}+He^4$. In this explanation of Bethe's one deals with a rigorous selection rule and it offers perhaps the most likely explanation of the sharpness of the γ-rays.

It should be observed, that in addition the disintegration into $(O^{16})^*+He^4$ must be made sufficiently improbable. It is unlikely that all $(O^{16})^*$ with an energy lower than $F^{19}+H^1-He^4$ have zero total angular momentum. It is, therefore, necessary to assume in addition that either all these $(O^{16})^*$ have zero angular momentum or else that the energy difference $(O^{16})^*-O^{16}$ is sufficiently high to make the alpha-particle energy low in comparison with the Coulomb barrier. The high intensity of the γ-rays indicates that the γ-ray emission occurs at least partly through $(O^{16})^*+He^4$ because otherwise it has to compete with proton escape which is appreciable at the higher energies. The observed γ-ray energy of 6 Mev indicates that $(O^{16})^*-O^{16}$ is at least 6 Mev and that the alpha-particle energy varies between 2.2 and 4.2 Mev in the experiments. For low energy protons there is no difficulty in making the broadening of the levels due to dissociation into $(O^{16})^*+He^4$ unobservably small and it is conceivable that some of the resonances at low proton energies have to do with γ-ray emissions in Ne^{20} as has been proposed by Bethe.[11] One would expect, however, that even at low proton energies there will be some γ-rays due to the $(O^{16})+He^4$ process and it is apparently impossible to infer the existence of a Ne^{20} level from these experiments.

For this explanation it is essential to have odd levels of even parity or even levels of odd parity in the observed energy range. In addition there is the possibility of using approximate selection rules for ordinary and isotopic spin.

It appears to be too difficult to make a direct calculation of the level systems in Ne^{20} at this stage. But something can be learned by comparing the above results with other experiments. This will be made first with the 440 kev resonance of Li^7+H^1. The half-value width of this resonance has been measured by Hafstad, Heydenburg and Tuve[4] and was found to be $\sim$11 kev. It is probable[12] that all of this width is due to proton escape, the alpha-particle disintegration of the compound nucleus is probably ruled out by the rigorous parity selection rule. On this view the protons in the reaction have angular momentum $L=0$. By use of the one-body picture the half-width can be expected to be[13] $\sim 2E/\int \bar{G}^2 d\rho$. Here $\bar{G}$ is r times the radial wave function for resonance normalized so as to have unit amplitude at $r=\infty$, $\rho=2\pi r/\Lambda$, $\Lambda=$proton wave-length. At resonance the function G outside the nuclear well is the irregular Coulomb function[14] G. For $r=3\times10^{-13}$ cm, $G^2\sim4.7$, $\rho\sim0.38$. The above formula gives with these values[12] a half-width $\sim$100 kev. Such a large value means essentially that the Coulomb barrier has little to do with the problem and that the resonance width in the one-body model depends considerably on the parameters of the model.[15] If 100 kev is taken for the resonance half-width on the one-body model there must be a further reduction by a factor 10 in the width due to the difference between the actual nucleus and the one-body

[11] H. A. Bethe, Rev. Mod. Phys. **9**, 69 (1937); see p. 232.
[12] Pages 510–512 of reference 4.
[13] G. Breit and F. L. Yost, Phys. Rev. **48**, 203 (1935). A more accurate formula is Eq. (32) in G. Breit and E. Wigner, Phys. Rev. **49**, 519 (1936).
[14] F. L. Yost, J. A. Wheeler and G. Breit, Phys. Rev. **49**, 174 (1936).
[15] By use of a different method, Bethe, Rev. Mod. Phys. **9**, 69 (1937), see p. 206, estimates a factor 10 for the effect of the barrier. Neither Bethe's estimate nor the present one nor the still higher estimates for 1,2 can pretend to be more than guesses at orders of magnitude.

model. This factor may be thought of as due to the necessity of a rearrangement in the Be^8 nucleus so as to liberate the proton. Neglecting the Coulomb barriers for $Ne^{20} \rightarrow O^{16}+He^4$ one would expect a width of ~ 3 Mev. On the assumption that the rearrangement factor is ~ 10 the expected width is ~ 300 kev. The observed widths of ~ 10 kev$\rightarrow 1$ kev leave a factor of $\sim 30 \rightarrow 300$ to be accounted for. This type of estimate is somewhat arbitrary since it has been supposed that the rearrangement factor is the same for proton and alpha-particle emission.

It has been pointed out by Oppenheimer and Serber[16] that the approximate conservation of ordinary and isotopic spin may be expected to serve as an approximate selection rule. A factor of the order of 100 for each of these spins may be expected. Because of the operation of one of these selection rules one may expect widths ~ 3 kev and because of the simultaneous operation of both one might get even smaller widths ~ 0.03 kev.

As has been emphasized by Bohr,[17] the many-body aspect of nuclei may be expected to lead to a great complexity of levels for the heavier nuclei and the same point has been brought out with less emphasis by Wigner and the writer.[18] Bethe's and Placzek's analysis of experimental material has shown that there is an important qualitative difference between heavy and light nuclei and that the number of nuclear levels as well as their sharpness increases with atomic weight. It is difficult to distinguish between a general increase in the complexity of internal motions and the operation of specific selection rules. The number of levels has to do only with nuclear complexity and could serve as a criterion if the calculation of the level density could be made reliably.

At 1.5 Mev incident energy the Coulomb barrier effects become small for protons. At the higher energies broadening due to proton escape may be expected to come in. It may be that lack of resolution of resonances between 1.8 and 2.2 Mev is due partly to this cause.

In addition to the sharp levels that have been detected in the gamma-ray experiments there may be present also other levels in the same energy range of the continuum. Experiment shows that from 0.3 Mev to 0.4 Mev there are practically no gamma-rays emitted in regions between resonance peaks. It must be concluded that the broader levels do not lead to as strong γ-ray emission as the narrow levels or else that there are no broad levels in this region. For this energy range one may neglect proton escape as a cause of broadening and the width due to radiative transitions in Ne^{20} is also negligible. One may consider as causes for the width the possible dissociations into normal $O^{16}+He^4$ or else into $(O^{16})^*+He^4$ or finally into $O^{16}+(He^4)^*$. The observed energy of the γ-rays makes the latter possibility unlikely.

Levels having a large width due to dissociation into normal $O^{16}+He^4$ will not give rise to an observable background if their width is large enough. For such levels the competition with the process responsible for γ-ray emission will be too severe. Thus if there were a level present in this energy region with a width of 300 kev the γ-ray intensity due to it would be less than that in the observed peaks in the ratio 1 : 30. In this energy region such an intensity is too difficult to observe. The background from 1.0 Mev to 1.3 Mev has a definite structure and produces the impression of having a rising continuation from 1.5 Mev to 1.8 Mev. It is impossible to tell whether it is partly built up of diffuse levels. It may be partly due to levels that dissociate into normal $O^{16}+He^4$ with an intermediate probability and which, therefore, emit weaker γ-rays.

The dissociation into $(O^{16})^*+He^4$ should give a cause of broadening that varies strongly with the energy available for dissociation. By use of the atomic masses of Bethe and Livingston the energy available (Q value) is found to be 8.2 Mev. If we attribute 6 Mev to the γ-ray, the alpha-particle energy is found to vary from 2.2 Mev to 4.2 Mev in the experiments, which corresponds roughly to a factor 50 in the penetration through the barrier. There may be important effects due to the character of the nuclear levels besides.

[16] J. R. Oppenheimer and R. Serber, Phys. Rev. **53**, 636 (1938).
[17] N. Bohr, Nature **137**, 344 (1936).
[18] G. Breit and E. Wigner, Phys. Rev. **49**, 519 (1936). See pp. 528, 530.

The small intensity at energies close to the first resonance must be due partly at least to the large barrier effect on the proton. The large yield of γ-rays at high energies indicates successful competition with dissociation into $O^{16}+He^4$. It suggests the origin of these γ-rays as due to $(O^{16})^*\rightarrow O^{16}+h\nu$. The apparently diffuse structure of the levels at the highest energies may be caused partly by the increased width due to dissociation into $(O^{16})^*+He^4$ as well as the broadening due to proton escape.

In conclusion it must be emphasized that the above considerations are speculative.

The authors are indebted to Professor G. Breit, Professor H. B. Wahlin, and Professor L. R. Ingersoll for advice and support, and to the Wisconsin Alumni Research Foundation for financial assistance.

SEPTEMBER 15, 1938 PHYSICAL REVIEW VOLUME 54

The Transmutation of Titanium by Th C′ Alpha-Particles

W. L. DAVIDSON, JR. AND ERNEST POLLARD
Sloane Physics Laboratory, Yale University, New Haven, Connecticut

(Received June 30, 1938)

Protons have been observed from the bombardment of titanium by Th C′ alpha-particles. They are probably due to the reaction $Ti^{48}+He^4\rightarrow V^{51}+H^1$. Three groups of protons are found corresponding to nuclear energy change $[Q]$ values of $+1.10$, 0.00 and -3.63 Mev. The separation of the last two groups is abnormally great. Combined with Dempster's value for the mass of Ti^{48}, the results lead to a mass of 50.9598 for V^{51}.

INTRODUCTION

TITANIUM, under bombardment by high energy alpha-particles, has been found to give a considerable yield of protons. The magnitude of the yield seems to require that the following reaction is responsible:

$$Ti^{48}+He^4\rightarrow V^{51}+H^1+[Q]$$

where $[Q]$ represents the nuclear energy change which takes place in the process.

We have investigated the transmutation protons arising from this reaction. Two different geometrical arrangements were used; first, an arrangement whereby the protons ejected at 90° to the incident alpha-particle are detected; and second, one in which the emergent proton and incident alpha-particle are in the same direction. Absorption curves have been obtained for both arrangements. Any definite "steps" in such a curve may be interpreted as representing energy levels in the residual nucleus, and by finding the nuclear energy change [Q value] corresponding to each group of protons, the spacing of these energy levels can be found. The recent publication by Dempster of a value for the mass of Ti^{48}, combined with the Q value corresponding to the limiting energy of the protons, should enable us to use this reaction to calculate the mass of V^{51}. The reaction is of additional interest since vanadium has an excess of five neutrons over protons in its nucleus. No other element studied has such a high excess of neutrons and hence any anomalies found might be considered significant.

APPARATUS

The apparatus used has been described in earlier papers.[1,2] A few minor additions have been made, which tend to make the apparatus more nearly automatic in operation. In its present state, an all night run, involving ten changes of absorption foils, may be carried through with no attention required after it is started. The proportional counter was filled with argon at one atmosphere of pressure and operated

[1] C. J. Brasefield and E. Pollard, Phys. Rev. **50**, 296 (1936).
[2] E. Pollard and C. J. Brasefield, Phys. Rev. **50**, 890 (1936).