Resonances in the Disintegration of Fluorine and Lithium by Protons

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The resonances in the emission of gamma-radiation from fluorine bombarded by protons have been studied from 300 kev up to 850 kev. Resonances were observed at 334, 479, 590, 660, and 820 kev with width at half-intensity, respectively, of 3.2, 2.6, 37, 7.5, and 8.3 kev. The absolute cross sections at resonance were found to vary from 0.4×10^{-26} cm^2 for the resonance at 590 kev to 5.9×10^{-26} cm^2 for the resonance at 334 kev. These results and previous results for the resonances at higher energies were compared to the single level dispersion formula, and the values of partial widths due to proton re-emission were found to vary from 10 volts at the 1076-kev resonance to 5.7 kev for the 1363-kev resonance.

The resonance in the emission of 17-Mev gamma-radiation from lithium bombarded by protons at 440 kev was found to have an experimental width of 14 kev. The cross section for the reaction at the peak of the resonance is 7.2×10^{-27} cm^2. The resonance curve is not symmetrical and cannot be explained by the single level dispersion formula.

1. INTRODUCTION

MOST of the light elements are known to give gamma-rays when they are bombarded with protons. The intensity of gamma-radiation from most of the light elements exhibits resonance phenomena; near resonance the amount of gamma-radiation is much greater than for neighboring energies. A great deal of work has been done to locate the positions of the resonance levels;[1] however, until recently the widths of most of the resonances were unknown because of the limits in resolution of the apparatus for accelerating the protons. The natural widths of the resonance levels are important in finding out the nature of the levels of the nucleus. Furthermore, the absolute cross section for disintegration at resonance can only be determined if the apparatus used has greater resolution than the natural width of the resonance. The combinations of width and cross section at resonance are useful in learning about the states of the intermediate nucleus.

Recently Bennett, Bonner, Mandeville, and Watt[2] have studied the resonances in the disintegration of fluorine by protons with an apparatus of improved resolution. Gamma-radiation with a quantum energy of 6.2 Mev results from the disintegration of F^{19} by protons according to the following reaction:

$$\begin{aligned} &F^{19}+H^1\rightarrow {}^*Ne^{20}\rightarrow {}^*O^{16}+He^4+1.74\text{ Mev.}\\ &{}^*O^{16}\rightarrow O^{16}+\gamma+6.2\text{ Mev.}\end{aligned} \quad (1)$$

These authors have reported the emission of gamma-radiation in the energy interval 800 to 1400 kev, and they found resonances at 820, 862, 890, 927, 1076, 1122, 1161, 1274, 1335, and 1363 kev. The resonances had widths which varied from less than 1.8 kev to about 100 kev. In case the resonances are well separated, the single level dispersion formula[3] applies, and the cross section for disintegration is given by the relation:

$$\sigma=\frac{\pi\lambda^2(2J+1)}{(2s+1)(2i+1)}\frac{\Gamma_\alpha\Gamma_p}{[(E-E_0)^2+1/4\Gamma^2]}.$$

Where J is the total angular momentum quantum number of a particular compound state of $^*Ne^{20}$; Γ_p, Γ_α, and Γ are the proton, short-range alpha-particle, and total width of this state; E is the bombarding energy and E_0 is the proton energy at resonance; s and i are the respective spins of the proton and the F^{19} nucleus which are both equal to $\frac{1}{2}$. The height of the potential barrier of F^{19} for proton is 2.3 Mev, and the barrier of O^{16} for alpha-particles coming out of the compound nucleus is 4.4 Mev. Since the barrier heights are considerably greater than the particle energies,

[1] L. R. Hafstad, N. P. Heydenburg, and M. A. Tuve, Phys. Rev. **49**, 866 (1936); **50**, 504 (1936); S. C. Curran, P. I. Dee, and V. Petrzilka, Proc. Roy. Soc. **A169**, 269 (1938); R. G. Herb, D. W. Kerst, and J. L. McKibben, Phys. Rev. **51**, 691 (1937); E. J. Bernet, R. G. Herb, and D. B. Parkinson, Phys. Rev. **54**, 398 (1938).

[2] W. E. Bennett, T. W. Bonner, C. E. Mandeville, and B. E. Watt, Phys. Rev. **70**, 882 (1946).

[3] H. A. Bethe and G. Placzek, Phys. Rev. **51**, 450 (1937).

the cross sections and widths of the resonance levels should be strongly influenced by the penetrability through the barrier.

Schiff[4] has been able to explain the observed variation in width and intensity by assuming a width without barrier of 100 kev for the emission of the short-range alpha-particles of reaction (1); he further assumed a width without barrier of 33 kev for the re-emission of the incident proton. Another reaction[5] which in some instances may compete with reaction (1) is the following:

$$F^{19}+H^1\rightarrow{}^*Ne^{20}\rightarrow O^{16}+He^4+7.95\text{ Mev.} \quad (2)$$

Schiff assumed a width without barrier of 33 kev for the emission of these long-range alpha-particles. The partial width of a resonance for alpha-emission or proton emission is found by multiplying the corresponding width without barrier by the penetrability. Schiff was able to explain the widths and intensities of the resonances from 800 to 1400 kev by a suitable choice of the angular momentum of the proton (0 to 4 units) and the angular momentum of the short-range alpha-particle (0 to 3 units).

The purpose of the experiments described in this paper was to extend the results of Bennett, Bonner, Mandeville, and Watt to the energy interval 300 to 800 kev and to measure experimentally the absolute cross sections at resonance. We also planned to study carefully the resonance for the emission of 17-Mev gamma-radiation when lithium is bombarded by protons. A pronounced resonance at 440 kev was observed by Hafstad, Heydenburg, and Tuve[6] with a width of about 11 kev as obtained from thick target excitation curves. The reaction responsible for the 17-Mev gamma-radiation is the following:

$$Li^7+H^1\rightarrow{}^*Be^8\rightarrow Be^8+\gamma+17\text{ Mev.}^{6a} \quad (3)$$

Experiments by Hudson, Herb, and Plain[7] indicate a small amount of 17-Mev gamma-radiation at energies above the resonance; the intensity of this radiation remains constant from 500 kev up to about 1500 kev. With the improved resolution of our apparatus, we planned to measure accurately the natural width of the level at 440 kev and to determine the absolute cross section for disintegration. We also wanted to study the shape of the resonance above and below 440 kev.

2. EXPERIMENTAL PROCEDURE

The apparatus which was used is the same as that described previously.[2] The potential of the pressure electrostatic generator was stabilized by modulating an electron beam which proceeded up the vacuum tube in the opposite direction to the protons. Some improvement was made in the spread in the energy of the protons beam by lowering the voltage in the ion source from 1800 to 600 volts, so that a mean spread in energy of the positive ions was probably reduced to less than 200 volts as they emerged from the ion source. The potential stabilizer was calculated to hold the voltage constant to less than 100 volts. The slit width of the magnetic energy selector was 0.015 cm, which allows a spread of energy of about 300 volts when operating at 330 kev, the position of the lowest resonance. Consequently, at the lowest resonance the over-all resolution of the apparatus was about 300 volts.

The gamma-radiation was detected by a Geiger counter which was shielded by $\frac{1}{4}$ in. of lead. The counter itself was made with a glass wall thickness of 0.2 mm and had a very thin silver coating as cathode. The front side of the counter was placed 1.2 cm from the target, and the sensitive region of the Geiger counter subtended 0.13 of the total solid angle. The efficiency of the counter in detecting 6.3-Mev radiations was calculated[8] to be about 3 percent. The counts resulting from the gamma-radiation were recorded on a mechanical counter by the use of a scale of 64. A current integrator was used to determine the number of protons which hit the target during the interval that a count of the gamma-radiation was made.

Targets were made by evaporating in a high vacuum ZnF_2 or lithium metal onto pure silver

[4] L. I. Schiff, Phys. Rev. **70**, 891 (1946).
[5] W. E. Burcham and C. L. Smith, Proc. Roy. Soc. **A166**, 176 (1938); J. F. Streib, W. A. Fowler, and C. C. Lauritsen, Phys. Rev. **59**, 253 (1941).
[6] L. R. Hafstad and M. A. Tuve, Phys. Rev. **48**, 306 (1935); see Hafstad *et al.*, reference 1; see Herb *et al.*, reference 1.
[6a] L. A. Delsasso, W. A. Fowler, and C. C. Lauritsen, Phys. Rev. **51**, 391 (1937).
[7] C. M. Hudson, R. G. Herb, and G. J. Plain, Phys. Rev. **57**, 587 (1940).
[8] H. Bradt, P. C. Gugelot, O. Huber, H. Medicus, B. Preiswerk, and P. Scherrer, Helv. Phys. Acta **19**, 77 (1946).

disks. The number of atoms per sq. cm was obtained by weighing the targets on a microbalance. In general, thicker targets were used for a general survey, and then the narrow resonances were investigated with thinner targets.

A calibration curve for the energy of the bombarding protons was made up from the known energy of the resonances at 334, 479, 660, and 862 kev[1] and the measured value of the current in the deflecting magnet for each of these resonances.

Experimental excitation curves were taken with increasing magnet currents to avoid troubles from the hysteresis of the iron. At the end of each period of observation the magnet current was increased to a fixed large value, and then the current was slowly decreased to zero.

The positions of resonances on succeeding days agreed with each other within 1 or 2 milliamperes out of a total current of approximately 2 amperes.

3. EXPERIMENTAL RESULTS

$F^{19}+H^1$

The first experimental run was made with a ZnF_2 target which had a weight of 11.5 micrograms per cm^2. This amount of material in the target produces a loss of energy of approximately 3.0 kev for 334-kev protons; the loss of energy in the target decreases to 2.1 kev at 660 kev. Over a thousand Geiger counts were observed at each bombarding energy. With proton energies far removed from a resonance, the background

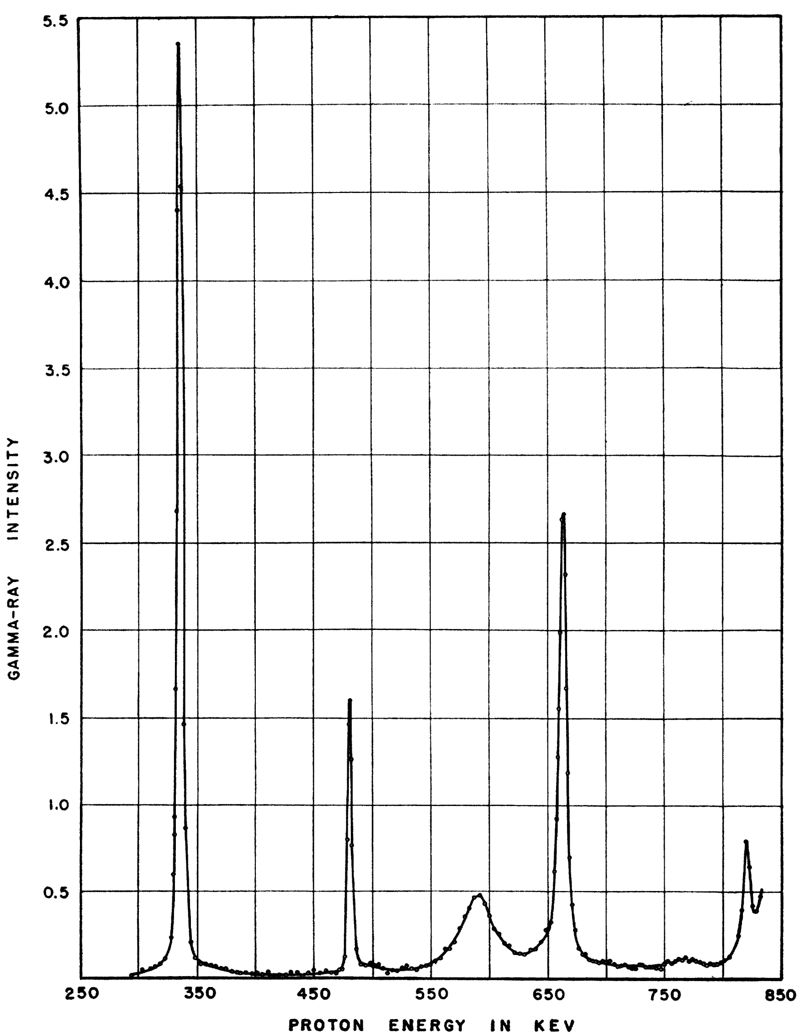

FIG. 1. Experimental curves of the intensity of gamma-radiation from a thin (11.5 micrograms per cm^2) target of ZnF_2 as a function of the energy of the bombarding protons.

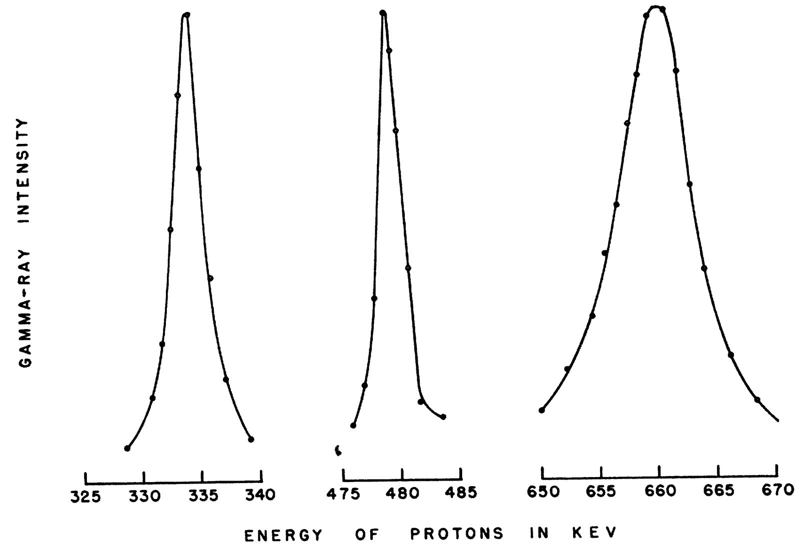

FIG. 2. Experimental curves of the intensity of gamma-radiation from a very thin (2.0 micrograms per cm^2) target of ZnF_2. The curve at the 660-kev resonance was obtained with the target whose thickness was 11.5 micrograms per cm^2.

counting rate of the Geiger tube was of the same order of magnitude as the rate resulting from gamma-radiation from the target; hence, it was necessary to subtract the background rate in order to obtain the true rate from the target. The data obtained with the first ZnF_2 target is given in Fig. 1. The experimental curve indicates resonances at 334, 479, 590, 660, and 820 kev. The experimental widths of these resonances are, respectively, 4.7, 3.6, 37, 7.8, and 8 kev. The natural width of a resonance and the absolute cross section for disintegration can be determined only if the loss of energy in the target and the spread in energy of the beam of protons is small in comparison to the natural width of the resonance. The true width and cross section for the resonances at 334 and 479 kev cannot be determined using the relatively thick target which was used to obtain the data of Fig. 1. A new ZnF_2 target which was much thinner and had a weight of 2.0 micrograms per cm^2 was used. The data obtained with this target are given in Fig. 2. The experimental width of the resonance at 334 kev was found to be 3.2 kev, and the width of the 479 level is only 2.6 kev. The widths and cross sections of the other resonances can be obtained from the data of Fig. 1. The broad resonance at 590 kev appears to be a singlet and has a width of 37 kev. The data concerning the resonance at 660 kev is plotted on a larger scale in Fig. 2. The experimental width of this resonance is 7.8 kev.

4. DETERMINATION OF ABSOLUTE CROSS SECTIONS

The absolute cross section for production of gamma-rays can be determined directly if one knows the following quantities: (1) the number of gamma-ray counts per microcoulomb of protons, (2) the solid angle which the Geiger counter subtends, (3) the efficiency of the Geiger counter, and (4) the weight and composition of the target. The most uncertain quantity which is needed is the efficiency of the Geiger counter for the 6.2-Mev radiation. One could use the calculated value of 3 percent in determining this cross section. However, it seems preferable to

TABLE I. Data concerning resonances in the emission of gamma-rays from $F^{19}+H^1$.

Resonance kev	σ at resonance $\times 10^{-26}$ cm^2	Experimental half-width kev	Width corrected for target thickness kev	$(2J+1)\Gamma_p$ calculated kev
334	5.9	3.2	3.2	0.10
479	2.9	2.6	2.6	0.06
590	0.4	37	37	0.13
660	2.5	7.8	7.5	0.18
820	0.7	8.5	8.3	0.07
862	25	5.2	5.2	1.6
890	0.9	4.8	4.8	0.05
927	8.8	8.0	8.0	1.0
1076	≥ 0.4	≤ 1.9	≤ 1.8	0.01
1122	0.8	4.1	3.7	0.05
1161	0.7	~ 130	~ 130	1.5
1274	1.9	19	19	0.7
1335	7.9	4.8	4.4	0.7
1363	19	15	15	5.7

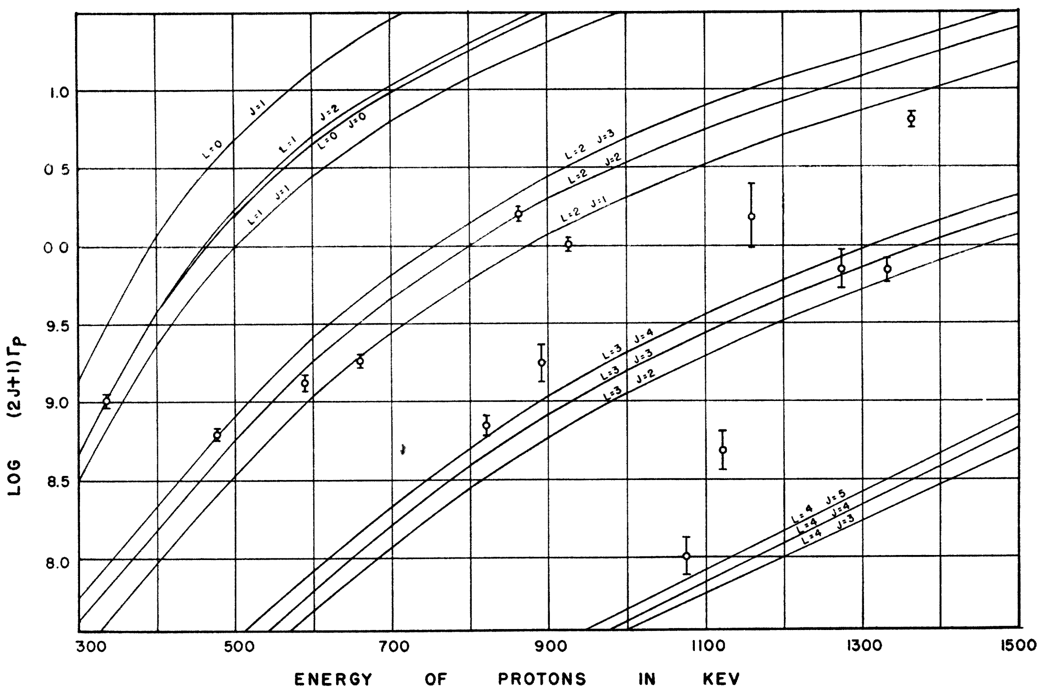

FIG. 3. The values of $\log(2J+1)\Gamma_p$ as a function of the energy of the protons. The points are those given in Table I with their probable errors indicated. The curves are theoretical ones with the value of $\Gamma_{p.w.b.}$ chosen so that the curve for $l=0$ and $J=0$ goes through the point at 334 kev.

make use of the data of Van Allen and Smith[9] who determined the absolute yield of gamma-rays from CaF_2 bombarded by 360-kev protons. These authors determined accurately the number of gamma-rays by counting the number of short-range alpha-particles which accompany each gamma-quantum. They obtained the result that there are 8.9×10^4 alpha-particles, and hence gamma-rays, per microcoulomb of protons. From the shape of the resonance at 334 kev we have computed the yield of gamma-rays from our target of ZnF_2 (11.5 micrograms per cm^2). The calculated value is 4.1×10^4 gamma-rays per microcoulomb. From the counting rate at 334 kev and the relative solid angle subtended by the counter, the efficiency of the Geiger counter was computed to be 3.7 percent; this value agrees well with what is to be expected. This efficiency will be the same for all the resonances we have investigated if the gamma-rays from each resonance have the same energy.

The absolute cross sections at resonance and the experimental widths at half-intensity are given in Table I. The values of the cross sections (σ) have also been calculated for the levels which have been previously investigated[2] between 800 and 1400 kev. In this table the broad peaks in the experimental curves at 1107 and 1161 kev have been classified as a single broad level instead of as two levels. The peak on the curve at 1107 probably is due to an interference effect produced by the narrow level at 1122 kev.

5. DISCUSSION OF RESULTS

The penetrabilities of the low energy alpha-particles are larger ($l=0$: 400 kev protons, $P_p=8.7\times10^{-4}$; 2.1 Mev α-particles, $P_\alpha=2.4\times10^{-2}$) than those of the protons; furthermore, one expects the width without barrier of the low energy alpha-particles to be greater than that of the protons.[4] This is because it would normally take a shorter time to concentrate a fraction of the nuclear excitation on the alpha-particle than to concentrate all the excitation energy on a proton. Now the partial width caused by the alpha-particle is equal to the alpha-particle

[9] A. Van Allen and N. M. Smith, Phys. Rev. 59, 501 (1941).

width without barrier times the penetrability:

$$\Gamma_\alpha = \Gamma_{\alpha.\text{w.b.}} \cdot P_\alpha,$$

and, similarly, the partial width due to proton emission $\Gamma_p = \Gamma_{p.\text{w.b.}} \cdot P_p$. From the argument above Γ_α will be considerably greater than Γ_p, and one can replace the total width Γ by Γ_α. The relation for the cross section at resonance now becomes:

$$\sigma = \pi \lambda\!\!\!^{-2}(2J+1)\frac{\Gamma_p}{\Gamma}.$$

Since σ, Γ, and $\lambda\!\!\!^{-}$ are known for each resonance, the value of $(2J+1)\Gamma_p$ can be calculated.

The calculated values of $(2J+1)\Gamma_p$ are given in Table I. The values of $(2J+1)\Gamma_p$ vary from 10 volts for the resonance at 1076 kev up to 5.7 kev for the level at 1363 kev. However, the values of $(2J+1)\Gamma_p$ do not increase smoothly with energy as would be expected if all the resonances were produced by protons with the same angular momentum. In Fig. 3, the values of the logarithm of $(2J+1)\Gamma_p$ have been plotted as a function of the energy of the bombarding protons. The largest value of $(2J+1)\Gamma_p$ which is possible at a given energy results when the proton has zero angular momentum. In this case the intermediate nucleus $^*Ne^{20}$ may have a total angular momentum of either 0 or 1 unit. There appears to be no way of deciding between these possibilities from the present data. If we assume that the resonance at 334 kev is produced by a proton with zero angular momentum and that the total angular momentum of the intermediate $^*Ne^{20}$ is zero, then the value of the proton width without barrier

$$\Gamma_{p.\text{w.b.}} = \frac{\Gamma_p}{P_p} = \frac{0.10 \text{ kev}}{2.7\times 10^{-4}} = 375 \text{ kev}.$$

This value of $\Gamma_{p.\text{w.b.}}$ is a factor of 10 greater than the value Schiff used in interpreting the earlier results. If we now assume that $\Gamma_{p.\text{w.b.}}$ is constant for all the states of $^*Ne^{20}$, we can calculate the values of $(2J+1)\Gamma_p$ for all the possible values of the orbital angular momentum ($l=0$, 1, 2, etc.) and total angular momentum J. These calculated curves are given in Fig. 3. A study of Fig. 3 indicates that disintegrations are probably produced by protons with angular momentum of $l=0$, 1, 2, 3, and 4. Several of the experimental points do not lie on the theoretical curves, and this may be interpreted as showing that the

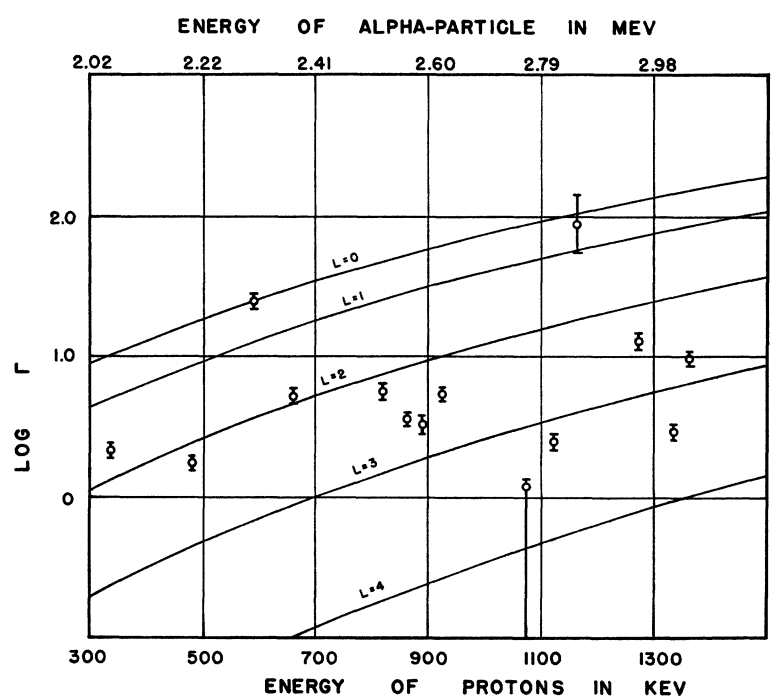

FIG. 4. The log of the width of the resonance levels (log Γ) plotted as a function of the energy of the protons and alpha-particles. The curves are theoretical ones with the value of $\Gamma_{\alpha.\text{w.b.}}$ chosen so that the curve for $l=0$ goes through the point at 590 kev.

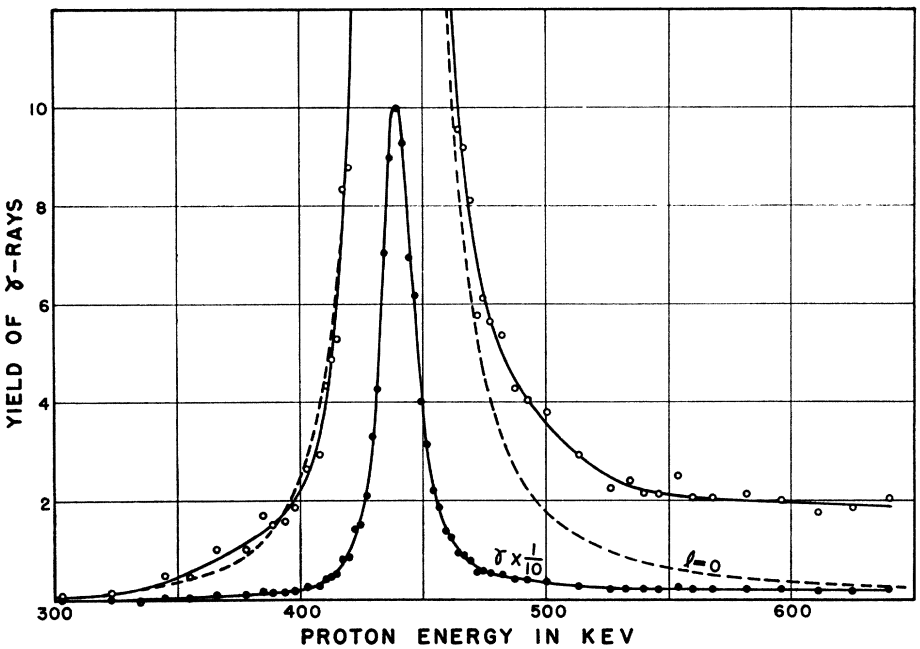

FIG. 5. The intensity of gamma-radiation from lithium as a function of the energy of the bombarding protons. The dashed curve is a theoretical one calculated for protons with an angular momentum $l=0$.

proton widths without barrier vary somewhat from level to level—perhaps by at least a factor of 2. This variation of $\Gamma_{p.w.b.}$ is not surprising as a nuclear structure factor varying from level to level might be expected. For a given value of l, one would not expect that $\Gamma_{p.w.b.}$ would show a trend with the energy. On the other hand, the value of $\Gamma_{p.w.b.}$ might be a function of the angular momentum of the protons.

A similar analysis can be made of the total widths of the resonance levels, using the approximation that the total width of the level is nearly equal to the partial width due to the alpha-particle (Γ_α). In Fig. 4, the logarithms of the total widths of the levels have been plotted as a function of the energy of the alpha-particles (E_α). The values of E_α are calculated from Eq. (1) for each value of the bombarding energy of the protons.

The level which occurs with a proton energy of 590 kev is considerably wider than other levels of about the same energy and consequently corresponds to alpha-particles leaving the $^*Ne^{20}$ with a minimum orbital angular momentum. It seems likely that this orbital momentum is $l=0$. With this assignment the value of the partial width without barrier of the alpha-particles can be found from the relation:

$$\Gamma_{\alpha.w.b.}=\frac{\Gamma_\alpha}{P_\alpha}=\frac{37\text{ kev}}{6.0\times10^{-2}}=610\text{ kev}.$$

The value of $\Gamma_{\alpha.w.b.}$ is about twice that of $\Gamma_{p.w.b.}$ which agrees with the theoretical argument given above. However, this width appears to be much larger than would be expected from the results[5] on reaction (2). The widths of some of the resonances in this reaction appear to be of the order of 25–50 kev. Since these alpha-particles have 8 Mev of energy the barrier penetration is unity, and the width without barrier is the same as the total width. It thus appears that the value of $\Gamma\alpha$.w.b. for the 8-Mev alpha-particles is only about 1/20 as great as for the 2-Mev alpha-particles. This would help explain why there are so few 8-Mev alpha-particles in comparison to 2-Mev alpha-particles.

In the discussion of the results above, the Doppler broadening from the thermal motion of the fluorine in the target has been neglected. In the case of a nucleus as heavy as F^{19} the Doppler broadening can be neglected unless the resonance is very narrow. For example, the Doppler broadening of the resonance at 1076 kev only amounts to approximately 140 ev. The Doppler broadening in lighter nuclei than F^{19} may be detectable for narrow resonances.

4. EXPERIMENTAL RESULTS

Li+H

Lithium targets were made by evaporating lithium metal in a vacuum onto silver disks. The targets were then weighed on a microbalance. This measurement was made about twenty minutes after taking the target out of the vacuum, and we assume that the chemical composition at this time was principally Li_2CO_3. The first target which was used had a weight of 24.1 micrograms per cm^2. The yield of gamma-radiation from this target was observed by means of a Geiger-counter when the bombarding protons had energies from 300 to 600 kev. The experimental results are given in Fig. 5. The resonance at 440 kev had an experimental width of 16 kev. The thickness of the target for 440-kev protons was estimated to be about 9.7 kev. A second target was used which was made in the same way; this target gave only $\frac{1}{2}$ as many Geiger counts per microcoulomb of protons as the first target, and its thickness is estimated to be 4.6 kev. With this second target the experimental half-width of the resonance at 440 kev was found to be 15 kev. The natural resonance width is estimated to be 14 kev from these results; the width of the excited level in Be^8 is $\frac{7}{8}$ of this width or 12 kev.

5. DISCUSSION OF RESULTS

The cross section for this reaction at resonance was calculated in the same way as that described above in the case of F+H. However, the efficiency of the counter was different in the case of the 17-Mev radiation from Li^7+H. From our value of the efficiency of the Geiger counter for 6.2-Mev radiation and from the shape of the theoretical curve of Yukawa and Sakata,[10] we estimated that the efficiency of the Geiger counter for this radiation was 11 percent. Since lithium has more than one isotope, only the number of Li^7 atoms present per cm^2 was used in this computation. The calculated cross section at resonance is 7.2×10^{-27} cm^2. There is a possibility of considerable error in this cross section because of the uncertainty in the exact chemical composition of the target at the time of weighing and in the efficiency of the Geiger counter.

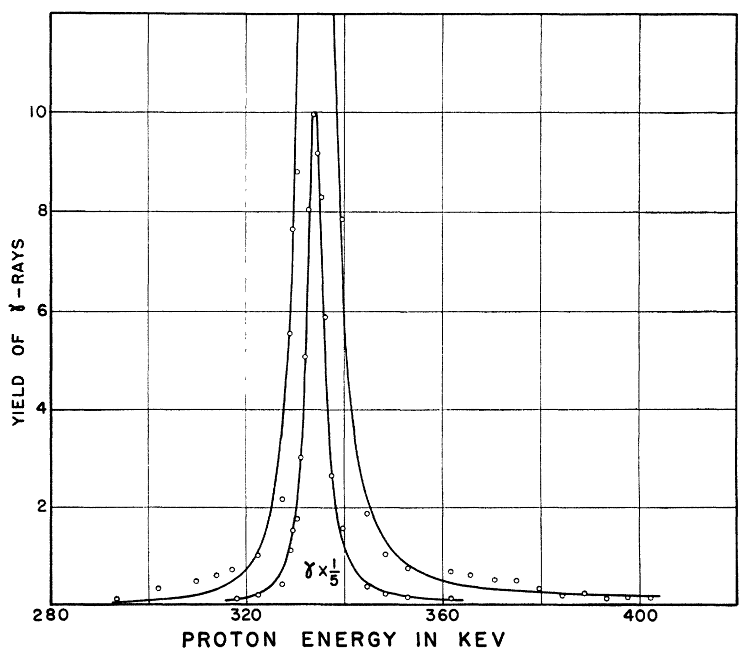

FIG. 6. The intensity of gamma-radiation from fluorine in the region of the 334-kev resonance.

[10] H. Yukawa and S. Sakata, Scientific Papers Institute of Physical and Chemical Research, Tokyo **31**, 187 (1937).

The resonance curve is shown in Fig. 5 on an enlarged scale; the asymmetry of the experimental curve is apparent. Figure 6 shows the curve for gamma-radiation from $F^{19}+H^1$ near the 334-kev resonance which was taken under similar conditions. This curve for the 334-kev resonance is nearly symmetrical and clearly shows that the asymmetry in the 440-kev resonance is real. In the energy region 550 to 600 kev, we observed 2 percent as much gamma-radiation as at 440 kev. This is in agreement with the 4 percent figure found by Hudson, Herb, and Plain, if allowance is made for the fact that they used a considerably thicker target of lithium. Hudson, Herb, and Plain also showed that the 17-Mev radiation remained essentially constant between 500 and 1500 kev.

If the penetrability of the incident protons increases rapidly with energy in the region of 400 to 1500 kev, a single resonance level might give such an asymmetrical shape. The dotted curve of Fig. 5 shows a theoretical resonance curve corrected for the change of penetrability for protons with $l=0$. This calculated curve is only slightly unsymmetrical. If an angular momentum of $l=6$ of the protons is used in this calculation, a rough fit can be obtained with the experimental data above 440 kev, but a very poor agreement is obtained below 440 kev. The penetrability for protons with $l=6$ is about 2×10^{-14} at 440 kev and is in disagreement by the order of about 10^{10} with the cross section for the production of gamma-rays.

The two competing reactions in the break-up of the excited $^*Be^8$ is the re-emission of a proton and the emission of a gamma-quantum. The time required for re-emission of a proton is expected to be much smaller than that required for the emission of a gamma-quantum. If the values of the spins of the proton and Li^7 are substituted in the equation for σ at resonance, the resulting value of the cross section is

$$\sigma=\frac{\pi\lambda\!\!\!^-{}^2(2J+1)}{2}\frac{\Gamma_\gamma\Gamma_p}{\Gamma^2}.$$

But since $\Gamma_p \gg \Gamma_\gamma$ this relation can be written

$$\sigma=\frac{\pi\lambda\!\!\!^-{}^2(2J+1)}{2}\frac{\Gamma_\gamma}{\Gamma}.$$

Since, σ, Γ, and $\lambda\!\!\!^-$ are known, Γ_γ can be calculated if the value of J is known. J is probably equal to 1 and then $\Gamma_\gamma=30$ volts. This corresponds to a time for the emission of a gamma-quantum of 2×10^{-17} sec.

The partial width of the level resulting from the emission of a proton (Γ_p) is very nearly equal to the total width Γ. Consequently, $\Gamma=\Gamma_p=\Gamma_{p.w.b.}\cdot P_p$ where $\Gamma_{p.w.b.}$ is the proton width without barrier and P_p is the penetrability of the proton. If the proton concerned has $l=0$, then $\Gamma_{p.w.b.}=12$ kev/0.27 = 44 kev. This value of $\Gamma_{p.w.b.}$ is several times smaller than that obtained in the bombardment of F^{19} by protons.

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