Cloud Chamber Studies of the Gamma-Radiation from Lithium Bombarded with Protons

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The gamma-radiation emitted when lithium is bombarded with protons has been studied by means of a cloud chamber operating in a magnetic field of 2000 gauss. The spectrum consists of at least eleven lines, the highest of which is 16 MEV. The voltage excitation curve for the gamma-radiation shows a maximum at 650 kv proton energy, and is very different from the excitation curve for the 8.4-cm alpha-particles emitted under the same conditions. An attempt is made to interpret these results. The experimental procedure and methods of measuring the cloud chamber tracks are also discussed.

INTRODUCTION

THE gamma-radiation emitted when lithium is bombarded with protons has been the subject of considerable discussion, mainly concerning its quantum energy, but in some instances concerning the existence of the radiation itself. The lack of agreement among experimenters working at various voltages as to the existence of the lithium radiation is, however, fully explained by the peculiar shape of the voltage excitation curve, which is not at all similar to the shape of the curve for the yield of long range alpha-particles produced under the same conditions of bombardment.[1]

Lauritsen and Crane[2] first measured the absorption coefficient of the radiation in lead and found it to be the same as that of gamma-radiation from radium, and hence supposed that its quantum energy was also the same, namely about 1.6 MEV. Later,[3] with the knowledge of the way in which the absorption coefficient for high energies is modified because of the creation of electron pairs, it was necessary to reinvestigate the absorption coefficient of the lithium radiation, with absorbers of at least two different atomic numbers. Lead and copper were used, and the combination of absorption coefficients found was such as to place them on the ascending branch of the curve at about 6.3 MEV, instead of on the descending branch at 1.6 MEV as previously supposed. At the same time Crane, Delsasso, Fowler and Lauritsen obtained Wilson cloud chamber photographs of the recoil electrons ejected from a thick lead plate by the radiation, and bent in a magnetic field. Their results indicated that the spectrum was complex, consisting of at least two lines, one at 4 and one at 12 to 13 MEV and this composite radiation was consistent with the observed value of the absorption coefficient which corresponded to 6.3 MEV.

It is mainly the results of a continuation of these cloud chamber studies which we propose to discuss in this paper.

APPARATUS

The vacuum tube used for accelerating the positive ions, the high voltage source and the ion source used in these experiments are essentially the same as described in a previous paper.[4] A horizontal Wilson cloud chamber 15 cm in diameter by 2 cm effective depth is operated at the center of a pair of Helmholtz coils capable of producing a magnetic field of 3000 gauss, constant to about 2 percent. In the present work fields up to 2000 gauss were used, requiring up to 180 amperes at 100 volts, hence to avoid excess heating the circuit is closed only for about 1 second, at the time of the expansion. By means of a system of solenoids and relays separated by long insulating strings the ion source is also operated in synchronism with the cloud chamber. All relays are actuated from a central contact drum, driven by a motor, and the sequence of events is as follows:

1st contact: Filament in ion source raised to emitting temperature; small amount of hydrogen (H^1 or H^2) admitted into ion source; magnetic field circuit closed.

[1] Henderson, Phys. Rev. **43**, 98 (1933).
[2] Lauritsen and Crane, Phys. Rev. **45**, 63 (1934).
[3] Crane, Delsasso, Fowler and Lauritsen, Phys. Rev. **46**, 531 (1934).
[4] Crane, Lauritsen and Soltan, Phys. Rev. **45**, 507 (1934).

2nd contact: Chamber expanded; anode circuit of ion source closed, producing ion current of 100 microamperes at target.
3rd contact: Arc light flashed; camera shutter opened.
4th contact: Everything off.

The chamber is allowed 15 seconds to reach equilibrium before the next expansion.

By operating the ion source intermittently, as described, it can be considerably overloaded during the short time it is actually used. Also the tube can be run at higher voltages (it will run steadily at 1000 kv with 100 microamperes intermittent ion current) because less gas is set free by ion bombardment of the inside of the tube and bombardment of the target. This has been found especially advantageous in using targets of chemical compounds which are decomposed into gases by the ion stream. When bombarding with deuterons a considerable saving of heavy hydrogen is effected, since the gas is allowed to flow into the ion source for only about one-fifteenth the total time of running.

Choice of Absorbing Material

In our first cloud chamber studies of the radiation from lithium a thick lead plate was used as the material on the inner wall of the chamber, from which the observed electrons were ejected. Because of the rapidly increasing probability of the creation of electron pairs with increasing quantum energy, quanta of high energy have a greater chance of ejecting electrons into the chamber from a lead absorber than quanta of low energy (all above 3 MEV). Therefore the high energy end of a gamma-ray spectrum will experience greater absorption, and hence be responsible for a greater number of electrons in the chamber than will the lower end of the spectrum. In addition, there is the possibility of measuring the combined energy of both members of many of the pairs, and this, plus 2 mc^2, should give directly the energy of the quantum which produced the pair. However, several effects attend the use of a heavy absorber which tend greatly to reduce the intensity of the upper end of the electron spectrum, and tend to destroy any line structure which may exist below the upper energy limit of the radiation. Some of these effects are listed below.

(1) The increased absorption for high energy quanta is due entirely to increased pair formation. Since the quantum energy (less 2 mc^2) is shared between the two members of each pair, with the greatest probability for equal division, the average energy of members of pairs is less than half the quantum energy, thus contributing little to the upper end of the electron energy spectrum, and, in addition, tending to mask any line structure within the spectrum.

(2) The probability of electrons suffering large radiative energy losses in passing through lead is much greater, per electron in the absorber, than it is in the case of lighter elements. Theory[5] gives the following energy loss per cm path for 5, 10 and 20 MEV electrons due to electron collisions and to radiative collisions with nuclei:

		5 MEV	10 MEV	20 MEV
H_2O	Radiation	0.07	0.16	0.36
	Collisions	1.98	2.15	2.32
Pb	Radiation	6.4	14.4	31.4
	Collisions	12.5	13.9	15.3

Because of this a large number of electrons originating below the surface in the lead absorber may lose a large and undetermined part of their energy, and their only effect is then to mask any line structure that may exist lower in the spectrum. Fortunately large radiative losses are usually accompanied by large angle deviations, and hence many of these electrons can be recognized and discarded in the measuring process.

(3) Pairs, of which both members are measurable likewise suffer radiative energy loss and scattering, so the total energy of the pair (plus 2 mc^2) is seldom equal to the full quantum energy. Nevertheless, this perhaps remains the best indicator of the quantum energy, where a lead absorber is used.

Hence in cases where good resolution is necessary to reveal the line structure of a spectrum, an absorber must be chosen which will produce, in the chamber, as large a ratio of Compton recoil electrons to pair electrons as possible, and also give rise to a minimum of radiative energy loss and large angle scattering.

We have plotted in Fig. 1, from theoretical data,[6] the energy spectra of negative electrons

[5] Bethe and Heitler, Proc. Roy. Soc. **A146**, 83 (1934).
[6] Data on pairs taken from Bethe and Heitler, reference 5.

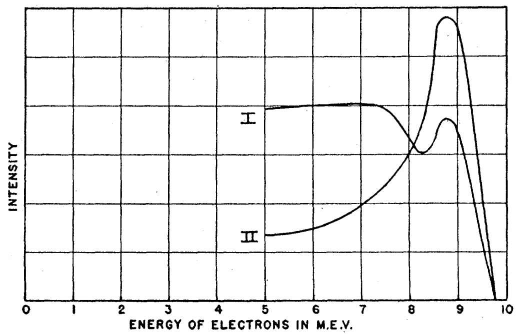

FIG. 1. Theoretical energy spectra of negative electrons which would be produced by a monochromatic gamma-ray of 10 MEV falling on a lead absorber (curve I), and on a glass absorber (curve II), each of thickness corresponding to 1 MEV stopping power for 10 MEV electrons, neglecting the effect of scattering.

which would be produced by a monochromatic gamma-ray of 10 MEV falling on a lead absorber and on a glass absorber, each of thickness corresponding to 1 MEV stopping power for 10 MEV electrons, neglecting scattering. The advantage of using an absorber of light material is evident from these two curves. For these reasons we have used the glass wall of the cloud chamber as the absorber in most of the work described in this paper.

Selection and Measurement of Tracks

The general character of the electron spectrum and resolving power depend to a large extent upon the selection of the tracks which are to be measured and recorded. The more closely the counting is restricted to tracks in the forward direction, the sharper will be the maxima and minima in the electron spectrum, but also the smaller will be the number of tracks measured. Such a selection should not influence the final value of the gamma-ray energy obtained except as to accuracy. In our present apparatus the spread in angle in the vertical plane is limited by the depth of the visible part of the chamber. If a track is visible for a distance of 2/3 the diameter of the chamber, it necessarily makes an angle of less than 7.5 degrees with the direction of the radiation. Arbitrarily, we allow about the same spread in angle in the horizontal plane (plane of the chamber). This rule of selection permits the measurement of a reasonably large number of tracks, and at the same time eliminates the following kinds of electrons which are undesirable:

(a) Compton recoil electrons which come off at a large angle to the direction of the quantum.

(b) Electrons which have suffered a large radiative energy loss and accompanying large angle deviation.

(c) Those members of pairs which receive only a small share of the energy of the quantum.[7]

A rigorous elimination of the above kinds of electrons is of course not accomplished, but the effect of such a selection is very much in the direction of increasing the resolution in the resulting electron spectrum. We have demonstrated this experimentally by comparing spectra obtained from the same photographs, using several different rules of selection of the tracks. Each track is inspected carefully for scattering by the gas along its path and rejected if it is visibly deflected. About 1/5 to 1/3 of the total number of measurable tracks in the chamber satisfy the above requirements as to direction, etc., the fraction depending somewhat upon the hardness of the radiation. The calculated limits in energy of Compton electrons which fall within the cone of half-angle 7.5 degrees are given below:

Photon energy (MEV)	Compton electron energy (MEV)
5	4.75 to 4.40
10	9.75 to 8.05
15	14.75 to 11.30

Measurement of the tracks is accomplished by projecting the photograph of the chamber, full size, onto a card on which is drawn a series of circles varying in radius by 1/2 cm steps. The radius of the circle which most nearly fits the track is recorded.

Structure of the Gamma-Ray Spectrum

In accordance with the methods outlined in the preceding paragraphs we have measured a total of 1576 negative electron tracks and 57 pairs resulting from the lithium radiation, using a magnetic field of 2000 gauss and using the 5 mm glass wall of the chamber as the absorbing material. This has, theoretically, a stopping power of about 2.5 MEV for 10 MEV electrons. In some cases a ½-mm lead foil was fixed to the inner side of the glass wall, in order to obtain a greater number of pairs. The results obtained with only glass as the

[7] The average lateral component of energy of a member of a pair is mc^2, independent of the energy of the quantum.

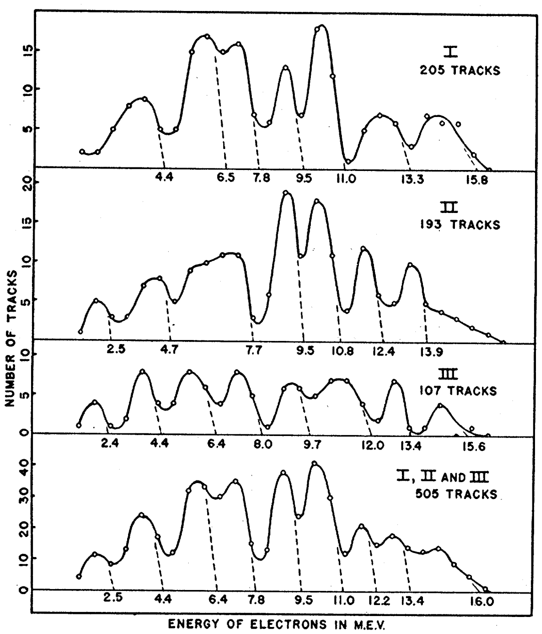

FIG. 2. Electron spectra resulting from three independent runs of 400 photographs each, plotted separately and added. The source of the electrons was the glass wall of the cloud chamber.

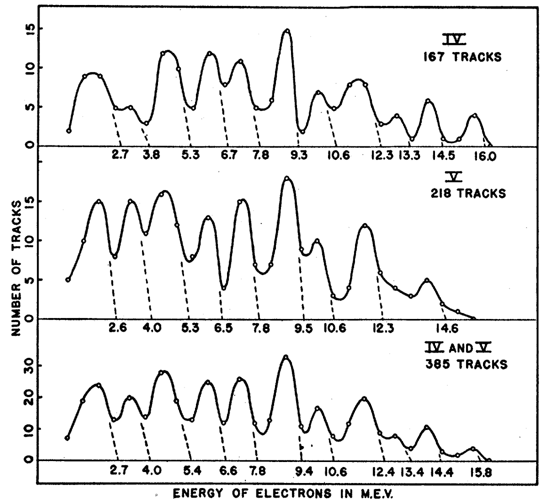

FIG. 3. Electron spectra resulting from two independent runs of 600 photographs each, plotted separately and added. The source of the electrons was the glass wall of the cloud chamber.

absorber are shown in Figs. 2 and 3. In Fig. 2 the results of three independent runs of 400 photographs each are plotted separately and then added together. In Fig. 3 two runs of 600 photographs each are plotted separately and added. It is seen that the principal features of the spectrum are the same in all the independent groups of data, and therefore are probably not due to statistical fluctuations. The fronts of the peaks are extended downward (dotted lines) and the energies corresponding to the intercepts noted on the diagram.[8]

The data obtained with the $\frac{1}{2}$-mm lead foil in the chamber were plotted in two groups, each consisting of the tracks from 800 photographs. The plots of these two groups, together with their sum, are reproduced in Fig. 4. In these measurements a $\frac{1}{2}$-cm radius of curvature (about 0.25 MEV energy) interval was used; hence the ordinates of the spectrum are only about half as high as those in the former set, where a 1-cm interval was used.

There are several possible ways in which the above data may be combined or averaged to give the probable values for the energies of the gamma-ray lines comprising the spectrum. The problem of extending the fronts of the peaks down to the axis is largely a matter of personal judgment, and subject to error, since the exact theoretical shape which the component peaks should have is not known. If all the data were plotted together as a single curve, the values which would be obtained for the energies of the gamma-ray lines would be dependent upon a single extrapolation. We have thought it more

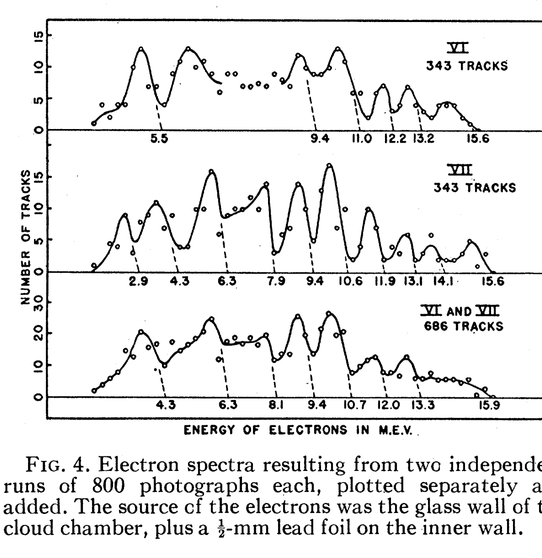

FIG. 4. Electron spectra resulting from two independent runs of 800 photographs each, plotted separately and added. The source of the electrons was the glass wall of the cloud chamber, plus a $\frac{1}{2}$-mm lead foil on the inner wall.

[8] It should be noted that the dotted lines should not necessarily be parallel, even for adjacent lines, unless the lines are of equal height and uniformly spaced.

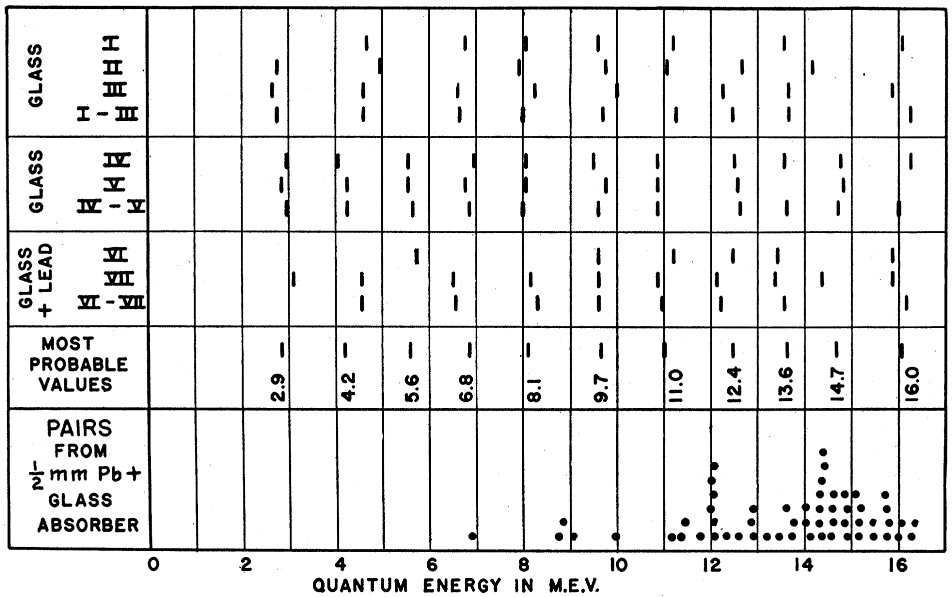

FIG. 5. Upper plot: Values of the gamma-ray energies, as indicated by each of the spectra in Figs. 2, 3 and 4. Lower plot: Total energies of pairs (2 mc² included), obtained when the ½-mm lead foil was placed in the chamber. Each dot represents a pair.

trustworthy, therefore, to draw the intercepts on each curve separately and average all the intercepts for a given line. In Fig. 5 are shown the values for the gamma-ray energies obtained from each spectrum, and also the average for each of the lines. All the values plotted in Fig. 5 are $\frac{1}{2}$ mc^2 (0.25 MEV) higher than the corresponding intercepts in Figs. 2, 3 and 4, as required by the theory of Compton collisions.

An independent check, especially on the upper limit of the spectrum, can be obtained from the electron pairs. From the photographs in which the chamber was lined with $\frac{1}{2}$-mm lead foil 57 pairs were found, both members of which could be measured with the required accuracy. The total energies of these pairs, with 2 mc^2 added in accordance with the theory of pair formation, are plotted in Fig. 5. Although the number of pairs is too small to give detailed structure within the spectrum, the upper limit is quite clearly indicated at 16 MEV, in agreement with the upper limit given by the plots of single electrons.

Division of Energy Between the Members of Pairs and the Ratio of Positive to Negative Electrons

We can obtain an interesting by-product of this work by plotting the pairs according to the fraction of the total energy carried away by one of the members, as shown in Fig. 6. This plot need not be restricted to the pairs from the lithium radiation, so we have included all the pairs we have accumulated from our measurements of various gamma-rays, and divided them into two groups according to total energy. A third curve is added to show the theoretical distribution for pairs produced by 10 MEV quanta, as given by Bethe and Heitler.[5] The shape of the curve is not sensitive to quantum energy in this region. It should be emphasized, however, that only the center portion of these plots can have any meaning, as far as checking the theory is concerned. Because of the experimental conditions, the chance of observing a pair in which one member has very low energy is small; therefore the ends of the experimental curve may be expected to drop off faster than those of the theoretical curve.

In order to obtain the ratio of the numbers of positive and negative electrons ejected from the glass absorber we took 400 photographs with a weak magnetic field (500 gauss), just sufficient to distinguish positives from negatives. In counting an arbitrary line was drawn across the projected image of the chamber perpendicular to the direc-

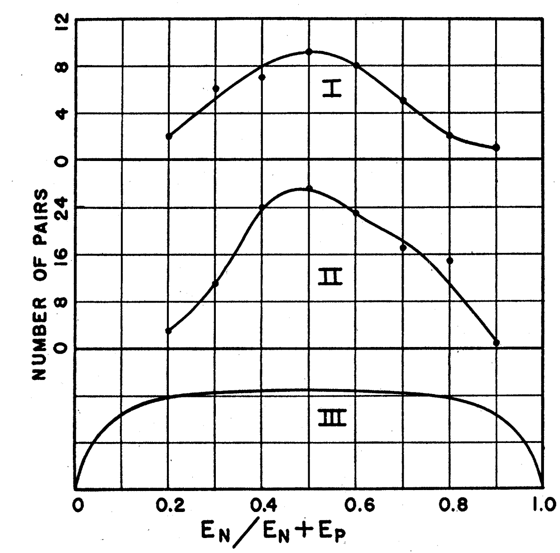

FIG. 6. Pairs, plotted according to the fraction of the total kinetic energy carried away by the negative number. Curve I: 42 pairs having total energy (2 mc^2 included) between 5 and 10 MEV. Curve II: 121 pairs having total energy between 10 and 16 MEV. Curve III: Theoretical distribution for 10-MEV pairs, according to Bethe and Heitler.

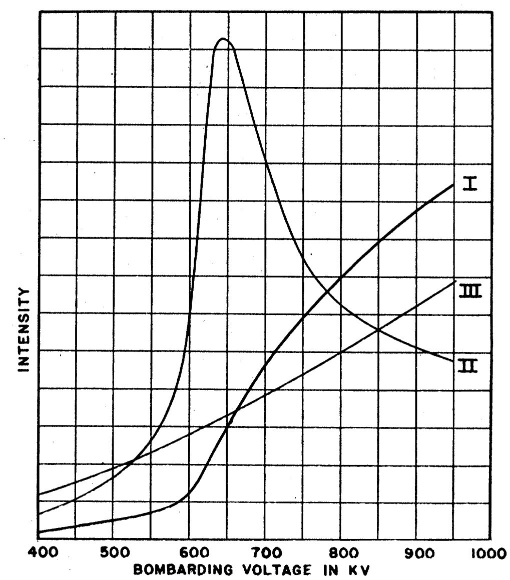

FIG. 7. Voltage excitation curves of the radiation from lithium bombarded with protons. Curve I: Experimentally observed intensity of gamma-radiation from a thick target. Curve II: curve I differentiated, to approximate a thin target. Curve III: Yield of 8.4-cm alpha-particles from a thick target, as obtained by Henderson.

tion of the radiation. All tracks which intersected the line were recorded according to polarity, but regardless of their energy or the angle at which they crossed the line. The use of a very low field eliminates the ambiguity about the polarity of tracks of low energy, which, in a strong field, would appear as half circles beginning and ending on the same side of the chamber. The ratio of positives to negatives obtained is not entirely independent of the rules adopted for counting, because the angular distribution of members of pairs and of Compton electrons is not exactly the same, and at best a very limited solid angle can be made use of. The result of the count was 408 positives and 930 negatives. Only 60 positives had negatives visibly associated with them. Assuming, nevertheless, that each positive indicates the existence of a pair, the ratio of pairs to Compton electrons can be obtained simply. It is 0.78 pair per Compton electron. Calculating the ratio of pair absorption to Klein Nishina absorption for glass (taking 11 for the average atomic number) from Bethe and Heitler's theoretical curves, we find that the ratio 0.78 corresponds to 15 MEV radiation. Considering the actual spectrum of the lithium radiation, this value for the effective quantum energy seems rather high.

VOLTAGE EXCITATION CURVE

The curve for the variation of intensity of the lithium radiation with the energy of the bombarding protons was found to have a rather striking character, as shown in Fig. 7. The intensity was measured with a lead-lined ionization chamber, shielded with enough lead to exclude stray radiation from the tube. A thick[9] target of LiCl was used, and a target of $CaCl_2$ was also bombarded as a check on the possibility of an effect from chlorine, and found to give negative results. The curve, as obtained under our experimental conditions, is necessarily an integral curve, since both a thick target and an ion beam of heterogeneous velocities were used. By differentiating this curve we may derive a curve which represents approximately the results which would have been obtained from a very thin target. Correction for the heterogeneity in velocity of the ion beam is more complicated and is not attempted here, for the reason that it would not modify the essen-

[9] The LiCl on the surface of the target is decomposed by the ion beam, so that after a short time the target actually consists of a thin Li metal film on a LiCl background. The excitation curve resulting from this should then be considered as due to a "partially thin" target.

tial character of the curve. Although the ion beam is not monochromatic, there is a preponderance of ions having velocity near the maximum, as has already been pointed out.[4] The differentiated curve shows clearly a sharp maximum in efficiency at 650 kv, and a decreasing efficiency above that voltage. The possible meaning of this will be discussed in the following section. Henderson's[1] curve for the yield of 8.4-cm alpha-particles from lithium bombarded with protons is drawn in for comparison, but without regard to relative intensity.

Discussion of Results

Although the values of the energies of the various lines in the gamma-ray spectrum are not known precisely enough to permit theories to be made about series relations, something pertinent may be said at least in regard to the upper limit of energy. There can be little doubt that the observed effect is due to the lithium isotope of mass 7. No reaction can be imagined involving Li^6 which can release sufficient energy to make possible the emission of a 16-MEV gamma-ray. The reaction which gives the required energy is

$$Li^7+H^1+E_H \rightarrow He^4+He^4+17.0\text{ MEV}+E_H \quad (1)$$

where the 17.0 MEV is the energy available due to the difference in mass on the two sides of the equation, and E_H is the energy contributed by the bombarding proton, because of its kinetic energy.

Alpha-particles are the only products in reaction (1); therefore, if gamma-rays are emitted, it is reasonable to suppose that they come from an excited alpha-particle, and hence are characteristic of transitions between energy levels in the alpha-particle.[10] We shall therefore write the reaction with one of the alpha-particles excited to 16 MEV (indicated by a bar), and with the energy left over for kinetic energy indicated as before.

$$Li^7+H^1+E_H \rightarrow He^4+\overline{He^4}+1.0\text{ MEV}+E_H. \quad (2)$$

The experimental excitation curves show that the reaction occurs with greatest probability when the proton bombarding energy is 650 kv. The maximum in the differentiated curve is quite sharp and has a half-breadth of about 100 kv, although part of this breadth is undoubtedly instrumental. Such a behavior is clear indication of resonance, or the existence of a virtual quasi stable level for the products of the reaction at the corresponding energy, which is equivalent to saying that the product particles separate through a resonance tunnel. Using the energy of the protons at the observed resonance peak, we find from reaction (2) that the position of the quasi stable level for the two alpha-particles is at 1.5 MEV.[11] This will be a level for the system consisting of one excited and one normal, or of two normal alpha-particles, according to whether the separation takes place before or after radiation. Such a level is possible only if the height of the potential barrier between the particles is considerably greater than 1.5 MEV. A half-breadth as small as 100 kv for the peak in the excitation curve would be understandable if the barrier height were about 2.5 MEV. For two normal alpha-particles the data on the anomalous scattering of alpha-particles in helium[12] and on the disintegration of boron by protons[13, 14] indicate a barrier height between 1.6 and 2 MEV. This value seems rather low to account for the observed sharpness of the resonance, but our data for the excitation energy of the alpha-particle are hardly of sufficient precision to settle this point.[15]

Recently Hafstad and Tuve[16] have obtained, independently, the excitation curve for this reaction over about the same range of voltage, using a monochromatic ion beam and a thin target. Their curve exhibits a sharp maximum at 450 kv and a

[10] Lauritsen and Crane, Phys. Rev. **46**, 537 (1934).

[11] Where the mutual energy of the two alpha-particles is considered, only 7/8 E_H is available, on account of the kinetic energy imparted to the system as a whole.

[12] Rutherford and Chadwick, Phil. Mag. **4**, 605 (1927).

[13] Lauritsen and Crane, Phys. Rev. **45**, 493 (1934).

[14] Cockcroft, Int. Conf. Phys. London, Oct. 1934.

[15] An analogous separation of the two products of disintegration through a resonance tunnel is clearly exemplified in the excitation curve of the gamma-rays from fluorine bombarded with protons, obtained by Hafstad and Tuve[16] which shows maxima at 350, 600 and 800 kv proton bombarding energy. The gamma-ray energy is 5.5 MEV, and the reaction is probably

$$F^{19}+H^1+E_H \rightarrow O^{16}+He^4+\gamma+2.6\text{ MEV}+E_H.$$

The energy left over for kinetic energy is clearly not enough to make possible the escape of the alpha-particle over the O^{16} barrier, so it is reasonable that the three maxima correspond to resonance tunnels for the escaping alpha-particle.

[16] Hafstad and Tuve, Phys. Rev. **47**, 506 (1935).

steep rise beginning at about 800 kv and continuing to the end of their scale, which is 900 kv. Allowing for a possible difference in absolute voltage calibration between the two laboratories, the two sets of data are in good agreement. The second rise in Hafstad and Tuve's curve may indicate the process in which the two alpha-particles separate *over* their mutual barrier. However, it is not yet known whether this is a continued rise or another maximum like the first.

On the basis of theoretical estimates of the lifetime for radiation and for separation of the two alpha-particles, we must think of the radiation as being emitted predominantly after the excited alpha-particle has escaped from the field of the other alpha-particle. The gamma-rays are thus characteristic of a free alpha-particle, and only the probability of excitation will depend upon the mechanism by which the reaction occurs, and upon the temporary proximity of the two alpha-particles. For the time required for the separation of the two alpha-particles through the tunnel indicated by the above data we have to expect

$$T \sim \hbar/10^{-7} \sim 10^{-20} \text{ sec.}$$

On the other hand, the time required for the emission of a 16-MEV gamma-ray is

$$\tau = (\hbar/10^{-7}) \cdot (100) \sim 10^{-18} \text{ sec.},$$

assuming dipole radiation, which gives the shortest time. Thus if these estimates are to be believed, the time which the two particles remain together is very short compared to the lifetime for radiation. The gamma-rays thus come from an essentially unperturbed alpha-particle, and the peak in the excitation is to be attributed to resonance between the excited and the normal alpha-particle.

However, since this inference rests upon no very certain foundation, it is worth while considering an alternative limiting hypothesis: namely, that the radiation is characteristic of the composite unstable Be^8 nucleus, and that this nucleus has a lifetime long compared to the radiation time τ. This would make the process analogous to the capture of a proton on a quantized level by Be^9 or B^{11} and the subsequent emission of gamma-radiation (discussed in a succeeding paragraph), with the one important difference that the unstable Be^8 nucleus after radiation disintegrates into two alpha-particles. On this view it would be equally possible to attribute the resonance to the two normal alpha-particles which are left after radiation. In this case the theoretical estimates of both T and τ would be smaller by a factor of about 100. On this view it would be hard, however, to account for the complex character of the gamma-ray spectrum. If the ground level to which the system radiated were a quasi stable combination composed of two normal alpha-particles, the radiative transition down to this level would be about 100 times as probable as a transition to an intermediate level (which would presumably not be quasi stable for the two particles), and we should therefore expect only the 16-MEV line to appear with appreciable intensity. The situation is not helped by supposing the resonance to occur for the two particles before radiation, since if this were so we should expect the Be^8 to disintegrate readily after a part of its energy, corresponding to a transition to one of the intermediate levels, had been radiated. Both these mechanisms should give rise to a number of homogeneous groups of alpha-particles, related to the intermediate levels in the alpha-particle or in Be^8. No such groups have been found, and their absence must mean that the transfer of energy between the "inner" degrees of freedom of the alpha-particle and the inter alpha-particle kinetic energy must be slow compared to the rate of radiation. This again is theoretically very hard to accept, and furnishes a further argument against Be^8 as the origin of the gamma-rays.

Returning to the hypothesis that the gamma-rays come from the excited alpha-particle after disintegration, it is clear that their structure must be related to the energy levels of the free-alpha-particle. We must assume that the alpha-particle is nearly always excited initially to the full 16 MEV, and that it falls, usually by more than one step, to the ground state, thus giving rise to the observed softer lines. In order to account for the eleven observed lines it is necessary to assume that the alpha-particle has a series of at least seven levels between 0 and 16 MEV. It is not possible, however, to construct a unique level scheme on the basis of the present data.

If any level lower than the 16-MEV level could be excited, enough kinetic energy would remain for the two alpha-particles to clear any reasonable potential barrier, even for quite low proton bombarding voltages. The absence, experimentally, of any appreciable radiation at low voltages indicates that the excitation of the 16-MEV level is far more likely than that of any other. In part this can be accounted for by the effect of resonance between the two alpha-particles when this level is excited, but the relative probability of exciting this level seems rather large to be accounted for on the basis of the resonance alone. It might suggest that the 16-MEV level corresponds to an internal structure which is not radically different from that of Li^7 plus the bombarding proton. From the excitation curve, and from experiments made by Oliphant, we can be sure that lower levels are not excited with an efficiency greater than about 5 percent of that of the 16-MEV level at full resonance.

We have observed several instances in which a proton seems to be captured by a nucleus, forming a new nucleus in a quantized state, with subsequent emission of gamma-radiation only. In two of these, beryllium and boron, the upper limits of energy of the gamma-ray spectra are so high that they can be accounted for only by the processes $Be^9+H^1\rightarrow B^{10}$ and $B^{11}+H^1\rightarrow C^{12}$, respectively. The formation of N^{13} when carbon is bombarded by protons exhibits the characteristics of a capture process: Hafstad and Tuve[16] have found that the voltage excitation curve has one, and possibly two, maxima between 400 and 500 kv, and we have found indications of a weak gamma-radiation of quantum energy as high as 6 MEV, although very few tracks were obtained. The formation of C^{11} when boron is bombarded with protons is probably another capture process:

$$B^{10}+H^1\rightarrow C^{11}$$

and doubtless has a sharp maximum in the excitation curve, accounting at least in part for the lack of agreement as to the ratio of the proton and deuteron effects.

Assuming, as is indicated by the results presented in this paper, that even the lightest nuclei possess a large number of quantized energy levels spaced at rather small intervals, we should expect that in general within the available range of a half million volts in the bombarding energy we should find some particular energy at which the proton is captured by the bombarded nucleus with the emission of gamma-radiation.

The yields found for such processes indicate that the levels on which the protons can be captured are at least of the order of 10,000 volts wide. This is in rough agreement with the calculations of Breit and Yost.[17]

We wish to thank Professor J. R. Oppenheimer for many helpful discussions during the preparation of this paper. We are grateful to the Seeley W. Mudd Fund for the financial support of this work.

[17] Breit and Yost, Phys. Rev. **46**, 1110 (1934); **47**, 508 (1935).

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Intensities of Satellites of $K\alpha$

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By use of a Siegbahn vacuum spectrograph, the intensities relative to that of the parent line, were measured for the satellites of the $K\alpha_1$ line for elements in the atomic number range 16–29; but these intensities are in general much lower than those reported for the satellites of the line $L\beta_2$. The variation in this range is from approximately 0.7 percent to about 5 percent while the maximum found for the satellites of $L\beta_2$ was 52 percent. These results are in agreement with the prediction of Coster and Kronig as to low intensities for $K\alpha$ satellites; but, contrary to the Coster-Kronig theory, we find a possibility of a maximum of intensity which could not be explained on their assumption that the satellites originate in an Auger effect.