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Angular Distribution of Alphas from $Li^6(d,\alpha)\alpha$ and $Li^7(p,\alpha)\alpha$

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The intensity of the reaction $Li^6(d,\alpha)\alpha$ is observed to vary with angle as $1+A(E)\cos^2\theta+B(E)\cos^4\theta$, as expected from the Bose statistics of the product alphas, with $A(E)$ rising gradually beginning just below 1 Mev to a broad maximum a little below unity at a bombarding energy E in the neighborhood of 2 Mev. The coefficient $B(E)$ remains zero up to almost 1.5 Mev and rises to a positive value of about 0.35 at higher energies. The yield curve observed at right angles to the beam displays a sharp maximum at 0.75 Mev and there is evidence of approach to another peak at or just beyond the highest bombarding energy employed, 3.75 Mev. The substitution of a proportional counter for the ionization chamber used in earlier work has made possible improvement over our earlier observations of the angular distribution of the reaction $Li^7(p,\alpha)\alpha$ in the neighborhood of 3 Mev, where difficulty was experienced in the discrimination against pile-up of scattered protons, and the new results show a node in the curve for $A(E)$ at 2.7 Mev. A peak in the yield curve of this reaction is found at 3 Mev, which is about 3 Mev lower in the compound nucleus Be^8 than the lower peak observed in the reaction $Li^6(d,\alpha)\alpha$. There is great similarity in the trends of the angular distributions of the two reactions, but their coefficients $B(E)$ have opposite signs in the energy regions investigated, and both $A(E)$ and $B(E)$ rise from zero more gradually in $Li^6(d,\alpha)\alpha$ than in $Li^7(p,\alpha)\alpha$ as the bombarding energy increases from low values.

I. INTRODUCTION

BECAUSE the pair of alphas resulting from the reaction $Li^6(d,\alpha)\alpha$ and from the reaction $Li^7(p,\alpha)\alpha$ obey Bose statistics, their angular distribution is observed to display fore-and-aft symmetry, and it may be expanded in even powers of the cosine of the angle of deflection θ in the center-of-mass coordinate system:

$$Y(\theta)=Y(90^\circ)(1+A\cos^2\theta+B\cos^4\theta+\cdots).$$

The simplest theoretical discussion[1] of the Li^7 reaction, which considers only entering protons with the lowest possible angular momentum, accounts for the existence of a term in $\cos^2\theta$ but no higher terms. A more nearly complete theory,[2] treating also the entering protons in $Li^7(p,\alpha)\alpha$ or deuterons in $Li^6(d,\alpha)\alpha$ of somewhat higher angular momentum, accounts also for the term in $\cos^4\theta$. The angular distribution of the reaction $Li^6(d,\alpha)\alpha$ has been previously observed[3] only at 0.2 Mev and it was shown to be spherically symmetrical at this low bombarding energy. The $Li^7(p,\alpha)\alpha$ reaction has been observed in several laboratories,[4-7] with results not completely in accord in detail but consistently indicating a rapid rise of the coefficient $A(E)$ from zero at a small bombarding energy to a maximum near 1 Mev and a subsequent gradual decline. The most recent of those papers, which was by the present authors, disclosed the existence of a term in $\cos^4\theta$ having a coefficient $B(E)$ of order of magnitude $-\frac{1}{2}$ in most of the energy range from 1 to 3 Mev. That paper also showed that $A(E)$ falls off apparently toward zero just beyond the range of observation. In that work, the observations at the highest energies were rendered more uncertain than the rest because the range of the scattered protons is there about the same as that of the alphas, at least at some angle, and the scattered protons were so numerous that the possibility of their piling up to make pulses as large as the alphas was not completely eliminated. In view of the similarity and the relative simplicity of these two reactions, it seemed desirable to investigate the $Li^6(d,\alpha)\alpha$ at least as completely as the other reaction has been, and in the course of this work a rather definite improvement in

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[1] C. L. Critchfield and E. Teller, Phys. Rev. **65**, 10 (1941).

[2] D. R. Inglis, Phys. Rev. **74**, July 1 (1948).

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[6] S. Rubin, W. A. Fowler, and C. C. Lauritsen, Phys. Rev. **71**, 212 (1947).

[7] N. P. Heydenburg, C. M. Hudson, D. R. Inglis, and W. D. Whitehead, Jr., Phys. Rev. **73**, 241 (1948).

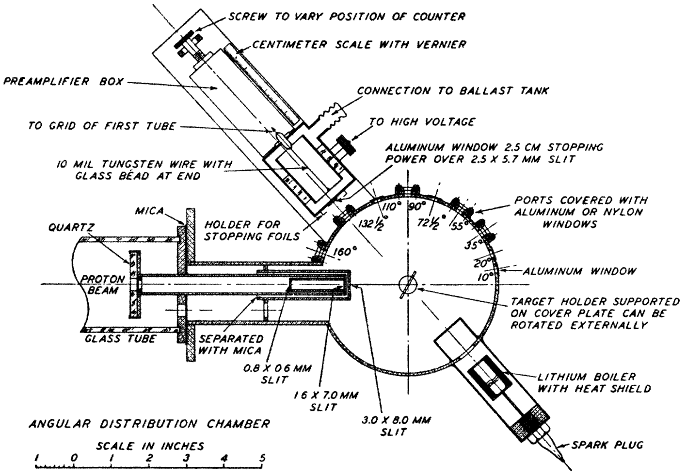

FIG. 1. Target chamber.

experimental technique was introduced which has made it possible to repeat with increased accuracy some of our earlier observations on $\mathrm{Li}^7(p,\alpha)\alpha$ in the high energy range.

II. APPARATUS AND TECHNIQUE

The present series of observations were made entirely with the large pressurized statitron, and most of the technique employed was closely similar to that described in our earlier papers.[7, 8] The only essential change was the substitution of a proportional counter for the shallow ionization chamber used in the earlier work. The pulses obtained from the proportional counter are of much shorter duration than those from the ionization chamber, so the probability of pile-up of the smaller proton pulses was greatly reduced.

The proportional counter is of rather conventional design, with a collecting electrode consisting of a 10 mil (0.025 cm) tungsten wire 2.5 cm long, supported from one end by a Kovar-seal insulator and protected at the other end by a small glass bead. A potential of 750 volts is applied to an insulated cylinder surrounding this, 2.5 cm in inside diameter and about 3 cm long. The particles enter through a 2×5 mm thin aluminum window in the end of the counter beyond the glass bead. The window is very near the axis, the nearest edge is a little less than 1 mm from the axis, and the alignment is sufficiently uncertain that particles might hit the wire. This does not intefere seriously with discrimination of particle energies, however, because the dimensions of the region of gas multiplication are much smaller than the dimensions of the window and only a very small fraction of the primary ionization takes place within the region of avalanche formation.

The proportional counter as we have been using it gives pulses of much shorter duration than the ionization chamber for several reasons, including the higher potential gradient in the significant region, the greater mobility in the reduced pressure and the smallness of the region (a few diameters of the inner wire) in which the significant potential drop takes place. But perhaps a more important cause of the slow pulses observed with the ionization chamber was that the amplifier was purposefully slowed down to filter out the high frequency noise and thereby increase the small pulse-to-noise ratio. This was done because most of the noise was high frequency noise after the microphonics had been eliminated by attention to the mechanical construction and mounting. The slow amplifier meant that positive ion current as well as electron current contributed to the pulses. With the proportional counter the pulses are large enough that the high-frequency noise makes no trouble. In our ionization chamber the tracks pass normal to the plane of the plates. In the proportional counter the incident particles are collimated parallel to the central wire, but in a region wide

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[8] N. P. Heydenburg and D. R. Inglis, Phys. Rev. **73**, 230 (1948). ***Erratum:*** An error occurred in an expansion of a transformation formula which was included supposedly for future convenience but was not employed in the calculations of that paper. The last expression for $g(E,\theta)$ on page 235 should read

$$g(E,\theta)=1-2(V/v_r)\cos\theta+(V/v_r)^2[(5/2)\cos^2\theta-\tfrac{1}{2}]+\cdots.$$

enough that they have various distances from it. Such a geometry would not be satisfactory for a simple ionization chamber with fast detection of electron motions only, because the contribution of an ion motion to the pulse size depends on the potential gradient through which it falls. (This is the so-called "electron collection," which really means *detection* of the *current* induced in the circuit by the *motion* of the electrons in the chamber.) Thus the pulse size would depend critically on the position of the particle path in the ionization chamber. In the proportional counter on the other hand the pulse size with a fast amplifier is a fairly reliable indication of the number of primary ions formed outside of the avalanche region, both because the primary electrons are a small fraction of all the electrons and because the primary electrons fall through a small potential difference outside the avalanche region. The important condition is that each primary electron forms an avalanche and each avalanche starts at about the same distance from the central wire. Within the proportional counter, the input circuit to the discriminator was given a time constant of about three microseconds.

The counter was filled with argon to a pressure of 9 cm Hg. As an aid to keeping the purity of the argon as constant as possible in spite of possible minute leaks, the counter itself was connected to a gas reservoir of about two liters capacity by a flexible metal tube, with manometers and filling valve mounted on the reservoir. During recent operation the gain of the proportional counter has remained sensibly constant for several weeks without refilling, so this precaution may have been unnecessary.

The proportional counter is mounted as shown in Fig. 1 on a carriage with a radial vernier screw mechanism which in turn is mounted on a supporting arm pivoted about an axis through the target, just as the ionization chamber was mounted in the earlier work. On the face of the proportional counter is a foil holder for the mounting of absorbing foils. The foils are used for the gross adjustments of range and the carriage is retracted to change the air path for fine adjustment.

The target backing used for the $\mathrm{Li}^7(p,\alpha)\alpha$ was thin Beryllium foil, of a thickness approximately 3 to 5×10^{-5} cm, in order to reduce the intensity of scattered particles to a minimum. This foil was cemented across a hole about 1 cm in diameter in a frame of rather thin sheet copper, and was mounted so as to permit rotation about an axis normal to the beam and to the plane of observation. The target backing for the $\mathrm{Li}^6(d,\alpha)\alpha$ reaction was thin silver leaf, stopping power about 1 mm. The target was normally set with its plane at about 66° from the beam direction. With it in this position the alphas could be observed at 10°, 20°, and 35° after traversing the backing. The window at 55° was considered too close to grazing and was ordinarily not used with the target in this position. Instead the target was turned to the complimentary 114° position for observation at this angle. The beam encounters the same effective target thickness at these two complimentary positions, as was verified by observing the same intensity for both target positions at the forward angles.

III. RESULTS

The excitation curves obtained by measuring the yield at 90° to the incident beam, as functions of bombarding energy, are shown for both reactions in Fig. 2. It is seen that the reaction $\mathrm{Li}^6(d,\alpha)\alpha$ exhibits a striking resonance at 0.75 Mev and shows evidence of the existence of another resonance very near the highest bombarding energy attained, 3.75 Mev. The reaction $\mathrm{Li}^7(p,\alpha)\alpha$ on the other hand displays but one

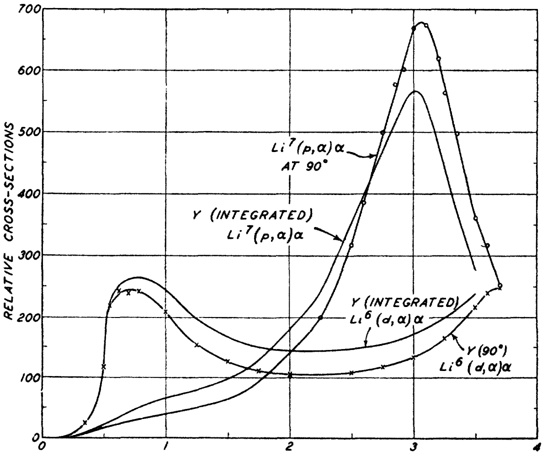

FIG. 2. Excitation curves for $\mathrm{Li}^7(p,\alpha)\alpha$ and $\mathrm{Li}^6(d,\alpha)\alpha$, obtained with thin evaporated targets. Both the 90° intensity and the average intensity are shown.

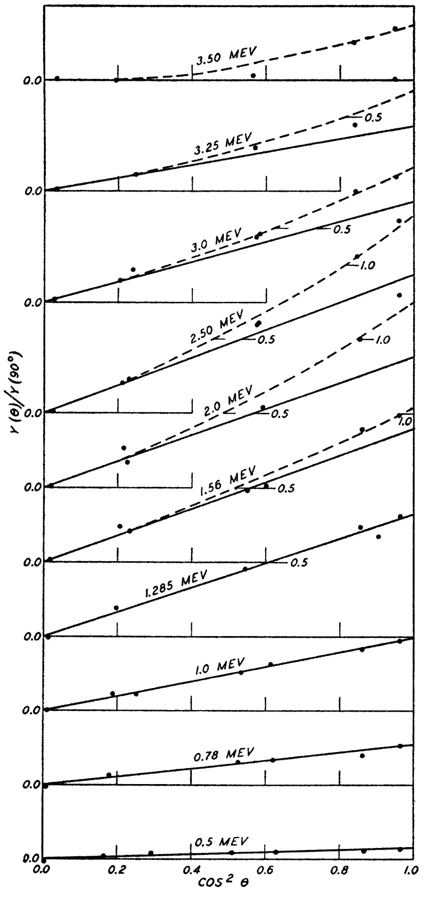

FIG. 3. Relative yields as functions of $\cos^2\theta$ for various deuteron energies for the reaction $Li^6(d,\alpha)\alpha$. The angle θ is the deviation from the deuteron beam in the center-of-mass system.

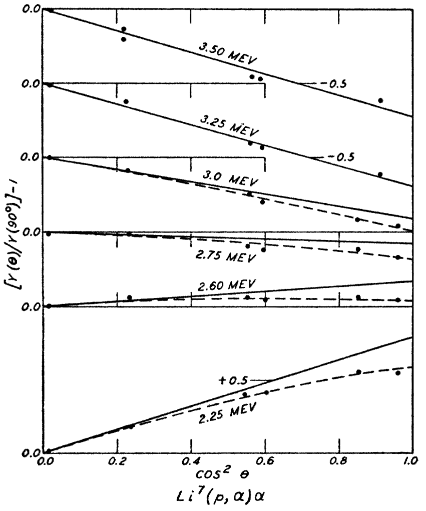

FIG. 4. Relative yields as functions of $\cos^2\theta$ for various proton energies for the reaction $Li^7(p,\alpha)\alpha$.

distinct resonance, at 3 Mev. The scale of ordinates in the figure is arbitrary because of the exact thickness of the thin targets, made by evaporation and used in the same vacuum, is unknown, but it is the same scale of nuclear cross sections for both curves, since this only requires knowledge of the (natural) relative abundance of the two isotopes in the target employed for intercomparison. The total yield curves, obtained from the 90° yields by integrating over all directions with the angular distributions reported below, are also shown in Fig. 2.

In Fig. 3 the angular distributions for $Li^6(d,\alpha)\alpha$ at the various energies are shown by plotting the observed yields, relative to the observed 90° yield, as dependent on $\cos^2\theta$. In such a plot a straight line would indicate that $B(E)$ is zero and the slope of the line would be $A(E)$. Each plotted point has been obtained by first varying the range adjustment enough to verify the position of the peak of the range curve, the bias being sufficient (in almost all cases) to count only alphas near the end of their range in the proportional counter, and then returning to take at least a thousand counts at the peak positions at all angles possible at a given energy. The angles and intensities have of course been transformed to the center-of-mass coordinate system.[8] Observations made at forward and backward angles having about the same value of $\cos^2\theta$ are plotted as nearby points, and the fact that they fall consistently on the same curve is a demonstration of the fore-and-after symmetry. It is seen that there is some scattering of the points, and this makes it impossible to determine $A(E)$ and $B(E)$ uniquely from them. Because of this inevitable uncertainty, we have simply drawn "by eye" a roughly parabolic curve which fits the points reasonably well. The slope of the tangent to this curve at $\cos^2\theta=0$ is then taken as $A(E)$ and the difference between the intercepts, at $\cos^2\theta=1$, of the curve itself and of this tangent is $B(E)$. The prevalently upward initial slope corresponds to positive $A(E)$ and the upward curvature to positive $B(E)$.

Similar results for the reaction $Li^7(p,\alpha)\alpha$ in the energy range between 2 and 3.5 Mev are shown in Fig. 4. These data are the result of repeating, with the more refined technique possible with the

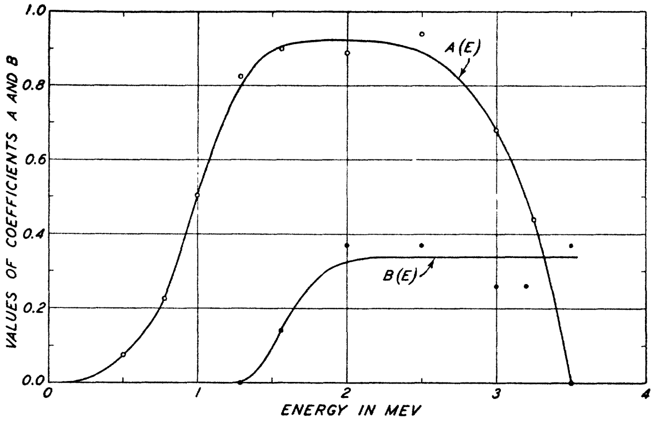

FIG. 5. Variations of $A(E)$ and $B(E)$ with bombarding energy E for the reaction $\mathrm{Li}^6(d,\alpha)\alpha$.

proportional counter, measurements made earlier with an ionization chamber.[7] Our earlier data were questionable just in this energy range, and particularly between 3 and 3.5 Mev, because here the scattered protons have about the same range as the alphas and it becomes more difficult to discriminate against pile-up when both kinds of particles are at the end of their range in the chamber. Even with the results observed with the proportional counter and shown in Fig. 4, it may be noted that the data are missing at some angles because of this difficulty.

The variations of $A(E)$ and of $B(E)$ with bombarding energy E are shown in Fig. 5 for the reaction $Li^6(d,\alpha)\alpha$ and in Fig. 6 for the reaction $\mathrm{Li}^7(p,\alpha)\alpha$. It is seen that the plotted values scatter some about the solid curves in Figs. 5 and 6, which were drawn in an attempt to fit the data as well as possible with reasonably smooth curves, but the arbitrariness in the simultaneous selection of $A(E)$ and $B(E)$ is sufficient that the observations may be considered compatible with the curves. In the case of the reaction $\mathrm{Li}^7(p,\alpha)\alpha$ theoretical formulas for the energy variation of $A(E)$ and of $B(E)$ have been given by one of us.[2] They are

$$A(E)=(C_0E^2+C_1E+C_2)/(E^2+C_3E+C_4), \quad (1)$$

$$B(E)=(C_5E^2+C_6)/(E^2+C_3E+C_4). \quad (2)$$

We find we can make a reasonable fit to the general trend of the observed results by selecting the arbitrary parameters as follows (with E expressed in Mev):

$$C_0=-1.75, \quad C_1=-2.8C_0, \quad C_2=0.27C_0,$$
$$C_3=-1.91, \quad C_4=2.15, \quad C_5=0.4, \quad C_6=-1.2.$$

The values of $A(E)$ and $B(E)$ resulting from this choice are shown as the dot-dash curve in Fig. 6. The solid curves were drawn to fit the points as well as possible without reference to the theory. It is seen that the fit is almost as good as was made in reference 2 to our earlier results by use of the same formulas but a different choice of parameters. The high-energy node which did not appear except by extrapolation in the earlier results has now been brought within the observed range. The observation of this node makes particularly apparent the inadequacy in this rather extended range of energies, of the earlier theory[1] based on entering p protons alone, since that theory predicts no node beyond the one at

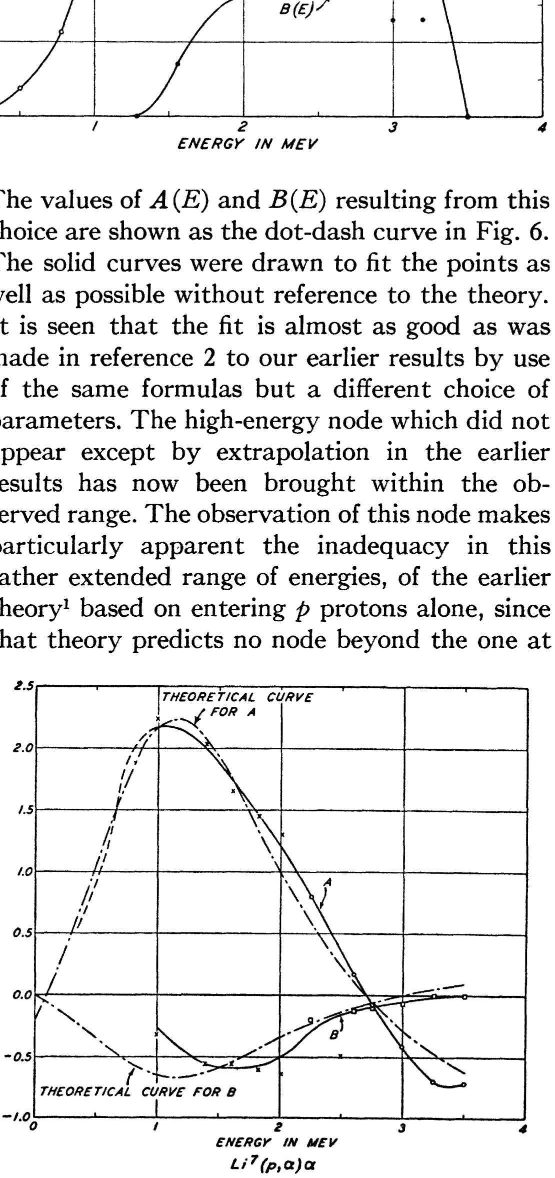

FIG. 6. Variation of $A(E)$ and $B(E)$ with bombarding energy E for the reaction $\mathrm{Li}^7(p,\alpha)\alpha$. The dot-dashed curves were obtained from theoretical formulas given by Inglis. The crossed points are taken from our earlier data (see reference 7). The circled points are the latest measurements.

low energy. It should also be noted that the present choice of parameters makes the intensity become negative at some angles at high energies beginning at about 7 Mev, so this choice would not be acceptable in a strict theory. However, Eqs. (1) and (2) result from a simplifying assumption concerning the barrier penetrabilities which is expected to be valid only in the region of fairly low energies, and is even being stretched in our application up to above 3 Mev. Since the theory with this assumption is not applicable at high energies, improper behavior there need not be used as a criterion. The assumption becomes gradually worse with increasing energy, and the choice of parameters has been influenced by a desire to defer the negative intensities to energies considerably above the present observations; otherwise a slightly better fit could have been obtained.

The theory is also based on the assumption that the reaction in this energy region is influenced mainly by two compound states, one narrow with $j=2$ and one very broad with $j=0$. Our excitation curve indicates a fairly narrow state of even parity in the neighborhood of 3 Mev bombarding energy, presumably the state with $j=2$, and the broad state would not be expected to give rise to an observable resonance. The reactions $\mathrm{Li}^7(p,\gamma)\mathrm{Be}^8$ and $\mathrm{Li}^7(p,n)\mathrm{Be}^7$ and the excitation of Li^7 by scattered protons indicate[9] the existence of four compounds states in the range of bombarding energies up to 2.5 Mev. Since we do not observe that they affect the reaction $\mathrm{Li}^7(p,\alpha)\alpha$ they are apparently states of odd parity. If we may use this as an indication of expected level density for the states of even parity also, we might consider the two states employed by the theory as rather few for so extended an energy range. This consideration leads us to suggest that the slight discrepancy between theoretical and experimental values of $A(E)$ above 2 Mev, which appears to be barely significant from the point of view of experimental accuracy, might be in part the influence of some higher compound state not included in the theory. This might in particular be true of the sudden upward bend in the experimental curve near 3.25 Mev, if this is real. The very slight discrepancy near 2.5 Mev gives no indication of another state since it could easily arise from inadequacy of the simplifying assumption concerning penetrabilities, or it could be eliminated by readjustment of parameters if no attempt were made to extend the fit above 3 Mev. It is satisfactory both that the assumptions made in the theory concerning the compound states are compatible with our observed excitation curve and that the theory, even with its assumption concerning penetrabilities, follows the general trend of the angular distribution data over so broad an energy range as well as it does.

We wish again to express our gratitude to Dr. Hugh Bradner of the University of California for supplying thin Be foils.

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[9] C. M. Hudson, R. G. Herb, and G. J. Plain, Phys. Rev. **57**, 587 (1940); Taschek and Hemmendinger, unpublished; W. F. Hornyak and T. Lauritsen, Rev. Mod. Phys. **20**, 191 (1948).

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Discharge Spread in Geiger Counters with Methane and Methane/Argon Fillings

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Further measurements with a split-cathode Geiger counter filled with methane and methane/argon mixtures are described.

I. INTRODUCTION

In earlier papers[1,2] some experiments on discharge spread caused by photon effects in divided cylinder Geiger counters have been described.

In these experiments it was shown that the absorption of photons capable of ejecting electrons from the cathode in self-quenching gases is not

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[1] J. D. Craggs and A. A. Jaffe, Nature **159**, 369 (1947).

[2] J. D. Craggs and A. A. Jaffe, Phys. Rev. **72**, 784 (1947).