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).

PHYSICAL REVIEW VOLUME 74, NUMBER 4 AUGUST 15, 1948

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).

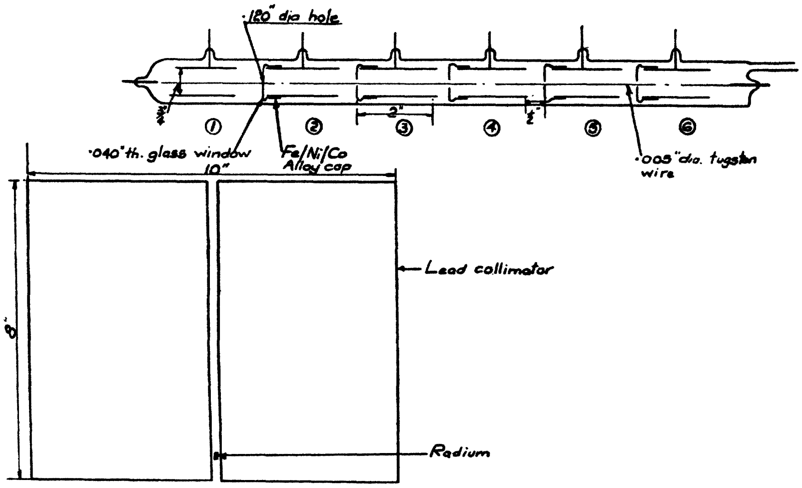

FIG. 1. 6-cylinder window counter.

complete. It must be emphasized, however, that this finding does not, in the least, invalidate the general and reasonable assumption that the discharge spreads along the wire in a Geiger counter because of photo-ionization in the gas near the wire with subsequent build-up of further avalanche processes. The same general type of mechanism is supposed to be responsible for streamer propagation in corona and spark discharges (Loeb).

The discharge propagation along the wire is accountable to absorption of highly absorbable radiations which, by virtue of the distances involved in the split-cathode counter work, cannot easily be responsible for discharge spread over a jump of some centimeters in length.

Two types of counter tube were described (*loc. cit.*), *viz.*: (a) one consisting of open-ended cylinders arranged in line along a common wire and (b) a counter containing cylinders with thick glass end windows through which the common wire passed. The windows served to collimate the photon beam from one of the end cylinders which was irradiated with an external (radium) source of gamma-rays. The gamma-ray beam was carefully collimated with a large lead block, so that the experimental arrangement was as shown in Fig. 1.

In the present work only the window-cylinder counter was used, and the preliminary results described with it in the earlier paper[2] were extended to include measurements with other gases.

So far as is known, in all similar previous work that has been made with counters (generally only two tubes have been used) to observe photo-ionization effects, the cathode photo-emission effect has not been separated from that resulting from photo-ionization in the counter gas.[3–5]

The purpose of the present paper is to provide further data required for the elucidation of the effects encountered in self-quenched ("fast") Geiger counters.[6, 7]

II. APPARATUS AND EXPERIMENTAL METHOD

The experimental arrangement is shown in Fig. 1. The counter tube consisted of 6 copper cylinders (initially cleaned with chromic acid and not deliberately oxidized) 2 inches in length, 0.75 in. in internal diameter, and spaced 0.5 in. apart. The windows (B.T.H. C40 glass) were 0.040 in. in thickness and had circular central apertures 0.120 in. in diameter surrounding the wire (0.005-in. diameter tungsten). Each cylinder except that at one end of the set had one window in it. The windows were necessarily made of an electrical non-conductor, and C40 glass was convenient for the purpose of sealing onto Fe/Ni/Co alloy caps which were slipped over the ends of the copper cylinders. The glass windows were sufficiently

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[3] E. Greiner, Zeits. f. Physik **81**, 543 (1933).

[4] S. C. Curran and J. E. Strothers, Proc. Camb. Phil. Soc. **35**, 654 (1939).

[5] F. Alder, E. Baldinger, P. Huber, and F. Metzger, Helv. Phys. Acta **20**, 73 (1947).

[6] S. A. Korff and R. D. Present, Phys. Rev. **65**, 274 (1944).

[7] M. E. Rose and S. A. Korff, Phys. Rev. **59**, 850 (1941).

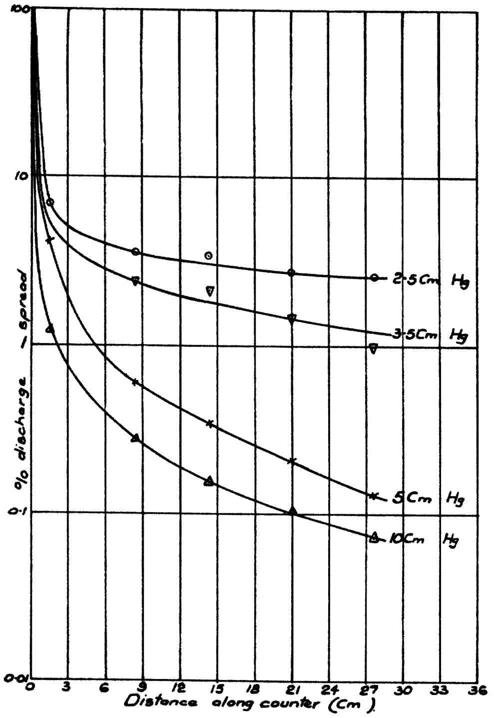

FIG. 2. Discharge spread in methane-filled split-cathodes counter (methane pressures are marked on the curves).

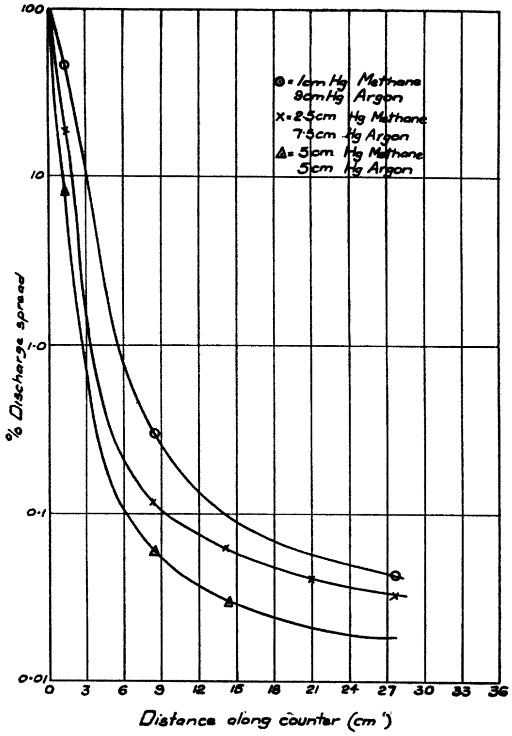

FIG. 3. Discharge spread in argon/methane-filled split-cathode counter.

thick to absorb effectively radiations whose wave-lengths were ~2000A or less (see Section IV).

The method was to irradiate an extreme cylinder and to count double coincidences between this cylinder and the others taken in turn. The circuits are briefly described in the earlier paper[2] and present no unusual features. In that paper also the precautions taken to eliminate random and cosmic-ray coincidences are described.

III. EXPERIMENTAL RESULTS

Figure 2 shows some data obtained with methane of good cylinder grade obtained from the Safety in Mines Research Board. The operating voltages were as shown in Table I.

TABLE I.

Gas	Press cm Hg	Starting voltage	Working voltage
Methane	2.5	1350	1400
	3.5	1420	1470
	5	1650	1700
	10	2000	2100
Argon/methane	9/1	1070	1720
	7.5/2.5	1250	1300
	5/5	1380	1480

Data for argon/methane mixtures are plotted in Fig. 3. The argon was of cylinder grade and contained about 1 percent of nitrogen with, of course, small traces of the other rare gases. Check experiments were made by varying the voltage on the intervening cylinders from zero up to values just less than the starting value (Table I), to ensure that the coincidence counts were not due to electrons diffusing from the first cylinder into those further along the counter tube. Since the photon flux from the irradiated cylinder should fall off with an inverse square variation with distance, the curves shown in Figs. 2 and 3 should be corrected, using the dimensions given in Fig. 1.

IV. DISCUSSION OF RESULTS

It must be stated at once that the conditions of operation for the methane and methane/argon fillings are not strictly comparable, in that the operating voltages are not the same for equal pressures. It is, unfortunately, not feasible to obtain such comparable conditions with counters, since the over voltage also should be adjusted in cases to be compared. No serious attempts were made in the present experiments to obtain conditions in which the absorption of quanta in argon/methane and methane could be compared, since the efficiency of production of quanta of a given energy, even in rigidly defined discharge conditions, of field strength, gas pressure, and gas purity, is not known.

The experiments are therefore intended to show only basic qualitative trends and to have relevance only to general counter theory. It is hoped in a later paper to describe experiments made with simple gases, with which more fundamental data may be obtained.

The paper of Korff and Present[6] discusses clearly the general mechanisms of photon quenching in fast counters. They point out that the general type of excitation process leading to photon production is different in the two cases of simple (atomic) and complex (polyatomic) gases since, for the latter, inelastic electron collisions will tend to give rotational and vibrational excitation, thus reducing the number of ultraviolet photons emitted, and even electronic excitation will generally result in decomposition of the molecule rather than photon emission. In a simple gas the proportion of excitations leading to emission of short wave-length quanta will be much higher than in a complex gas. In a mixture of gases such as argon ($V_i=15.7$ volts) and methane ($V_i=14.5$ volts) the energetic photons should therefore be produced mostly in the argon, despite its higher ionization potential, and the methane will serve to absorb these photons and thus prevent them from reaching the cathode of the counter.[6,7]

The continuous absorption in methane extends from about 1450A to shorter wave-lengths[8] and therefore, unless the work function of the cathode is less than about 8.5 V, photoelectric emission from the cathode will be unlikely. Evidence exists[2,9] that ordinary metals might in certain circumstances show such high work functions. Korff and Present[6] state that the ultraviolet photons from argon have wave-lengths lying between 1070A and 790A (corresponding to the level at about 11.5 ev and to the ionization potential which is 15.7 ev) so that methane could absorb them. It seems, however, that the argon spectrum would include radiations lying on both sides of the above band, but the main postulate, i.e., the ability of methane to absorb most of the argon radiations, seems reasonable. We do not propose, however, to discuss the photon energies obtainable by excitation in argon/methane mixtures.

A new feature of the results of Figs. 2 and 3 is the greater absorption of the radiations in argon/methane relative to methane even for the same total pressure and for a methane concentration of only 10 percent. Further, the partial pressure of methane (Fig. 3) affects the absorption only slightly. The absorption in 2.5 cm Hg methane is much less than with the same amount of methane added to 7.5 cm Hg argon.

Separate measurements with argon as filling gas (to be described in a later paper on photoionization effects in monatomic and diatomic gases) show that the absorption of argon radiations in argon is very small compared with that shown in Fig. 3. These results should be compared with those of Liebson,[10] who worked with argon/CH_2Br_2 and argon/C_2H_5OH. Liebson used a different experimental technique and did not eliminate the cathode effect.*

In the earlier paper the great reduction in discharges spread through a divided counter because of the use of windows was demonstrated. It is suggested that such a counter if made with glass beads on the wire[11] would show practically zero spreading and might be useful in applications to directional counting with split counters.[12]

V. CONCLUSIONS

The study of discharge spreading by photoionization of the gas in Geiger counters containing methane and methane/argon mixtures tends to support Korff's view that the photo-ionizing radiations are produced mainly in the argon and are quenched by the methane. The higher absorption and lower extent of discharge spreading in argon/CH_4, as compared with CH_4 only at the same pressure, would tend to show that absorption in argon is predominant when CH_4 is present,

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[8] H. Sponer and E. Teller, Rev. Mod. Phys. **13**, 75 (1941).

[9] R. Geballe, Phys. Rev. **66**, 316 (1944).

[10] S. H. Liebson, Phys. Rev. **72**, 602 (1947).

* This paper was written before Liebson's paper appeared, but it is thought necessary to refer to the latter.

[11] H. G. Stever, Phys. Rev. **61**, 38 (1942).

[12] W. E. Ramsey, Phys. Rev. **61**, 96 (1942).

but the probable differences in the spectra obtained in the two cases make detailed interpretation difficult.

VI. ACKNOWLEDGMENTS

The authors are indebted to Mr. F. R. Perry for his interest in and encouragement of the work and to Sir Arthur P. M. Pleming, C.B.E., D. Eng., Director of Research and Education, and to Mr. B. G. Churcher, M.Sc., M.I.E.E., Manager of Research Department, Metropolitan-Vickers Electrical Company, Ltd., for permission to publish this paper.

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Penetrating Particles in Extensive Air Showers

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Penetrating particles in extensive air showers have been studied at 4300- and 3260-m elevations. The particles capable of penetrating 14 cm lead are about 1 per 30 shower particles at 3260 m and 1 per 25 at 4300 m. The number of penetrating particles is reduced by a factor 1.8 when the lead is increased from 15.5 to 39 cm, and the density of the penetrating particles diminishes by a factor 1.7 between 4300 and 3260 m elevation. These facts imply the penetrating particles are very numerous and have too low average energy to be mesons coming from the top of the atmosphere. Further experiments show that they are not produced multiply in lead shields above the counters. This fact, together with the independence of their number on the atomic number of the absorber, seems to indicate they are not produced by photons.

SECTION A

In order to extend our knowledge about the penetrating particles in extensive air showers, experiments were performed last summer at Echo Lake and Mt. Evans, Colorado (elevations 3260 and 4300 meters, respectively), in which the particles of the showers were recorded with unshielded counters and with counters under lead. The counter and lead arrangement used for a large part of the data taken at Echo Lake and all of the data taken at Mt. Evans are shown in Fig. 1. For brevity in reference we shall call this experiment *A*.

In experiment *A* the area of the shielded counters was held constant at 293 cm^2 each, but the area of the unshielded counters was changed periodically among the values 48, 98, and 293 cm^2.

The counters had brass walls, $\frac{1}{2}$ mm thick, were one inch in diameter and were filled with a self-quenching gas mixture. Almost all were 16 inches in length and had an active area of 98 cm^2. The largest counter area referred to above, 293 cm^2, was composed by connecting three such counters in parallel. The smallest area, 48 cm^2, was obtained with single counters eight inches in length and one inch in diameter. The circuits and the counter plateaus were checked daily during the course of the experiments.

As Fig. 1 shows, the counter separations were about two meters. Cocconi, Loverdo, and Tongiorgi[1] have shown that the number of showers recorded with a counter arrangement similar to that of experiment *A* is not sensitive to changes of the counter-separation between two and eight meters.

The lead shielding the lower counters was composed of lead pigs, cut so as to nest tightly together, and covered with lead sheets. The counters were not perfectly shielded with lead at the ends, but the lead below, on the sides and above the counters was much longer than the counters themselves (see Fig. 1b). The smallness of the counter area facing the ends, the small solid angle of the openings and the low intensity at large zenith angles combine to make the relative probability of a shower particle entering the counter through the unshielded ends less than 10^{-3}. The lead below the counters was five

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[1] G. Cocconi, A. Loverdo, and V. Tongiorgi, Phys. Rev. **70**, 841 and 852 (1946).