bridge arms R_L constitutes the stabilizer load, while another arm is represented by the equivalent internal resistance of the stabilizer which is to be measured. By making R_2 equal to R_L, the desired internal resistance may be read directly by balancing with R_1. A low resistance secondary winding on the transformer furnishing a.c. voltage to the bridge confines the entire output voltage drop to the "load impedance" arm of the bridge, while the blocking condenser prevents direct current from flowing in the null detector circuit.

Formula (15) and the a.c. bridge just described furnish a convenient method for evaluating the stabilization ratio S_0. If a variable resistor, simulating R_r, is inserted between the rectifier and the stabilizer input, then the reciprocal of the slope of the curve obtained by plotting measured values of R *vs.* R_r (as in Fig. 2) will give S_0 directly if the correction terms in the parentheses of Eq. (15) are small or null. Values obtained from these measurements are in complete agreement with those determined directly.

For the direct determination of S we have employed the circuit illustrated diagrammatically in Fig. 14. This is a modification of the simple circuit for the measurement of the amplification factor of a vacuum tube and the circuit diagram is self-explanatory.

JANUARY, 1939 R. S. I. VOLUME 10

A Complete Geiger-Müller Counting System

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(Received August 1, 1938)

Constructional details are given of a complete Geiger-Müller counting system consisting of a stabilized high voltage supply, Neher-Harper coupling circuit and vacuum-tube scale-of-eight feeding a Cenco counter stage. The system is entirely a.c. operated. Its resolution time of 6.5×10^{-6} second allows it to follow the G-M circuit without counting losses. The counting losses in the Cenco counter stage are negligible for random input rates to the system up to 20,000–30,000 counts a minute.

INTRODUCTION

BECAUSE of recent advances in the circuits and recorders used with Geiger-Müller counters, complete G-M counting systems may be constructed which exhibit many improvements in design. It is hoped that the following description of a G-M system using a stabilized high voltage supply, Neher-Harper coupling and vacuum-tube scale-of-eight circuit will prove useful and time-saving to those having need of such an apparatus.

Because of the maze of new counting circuits which have recently been published, it is becoming a difficult problem to choose between the various designs which are possible. This is largely because sufficient data on the complete operating characteristics of such circuits are not yet available. It is very probable that certain circuits will find their best application in certain kinds of counting work. For these reasons, some discussion will be given of alternative and perhaps preferable methods which may be adapted to an apparatus of the type to be described without changing the general constructional plan.

The requirements for a complete G-M system may be rather arbitrarily set down according to attributes which have been found desirable and useful in this laboratory. Proceeding on this basis, we may list the following requirements. The apparatus should be completely a.c. operated. It should incorporate a stabilized and variable high voltage supply. It should incorporate a vacuum-tube scaling circuit and a vacuum-tube quenching circuit for the G-M tube. The scaling circuit should have a resolution time of 10^{-4} second or less.[1] These latter conditions allow fulfillment of the requirements of high counting speed, the limitation of counting losses to the G-M circuit itself, and a very high order of reliability, stability and permanence of operating characteristics. The system using the above vacuum-tube circuits will also be easily portable, low in cost, and have a low power drain. It will also be insensitive to line voltage variations, changes in temperature due to heating, and tube replacements. Some method of interpolation

[1] H. Lifschutz and O. S. Duffendack, Phys. Rev. **54**, 714 (1938).

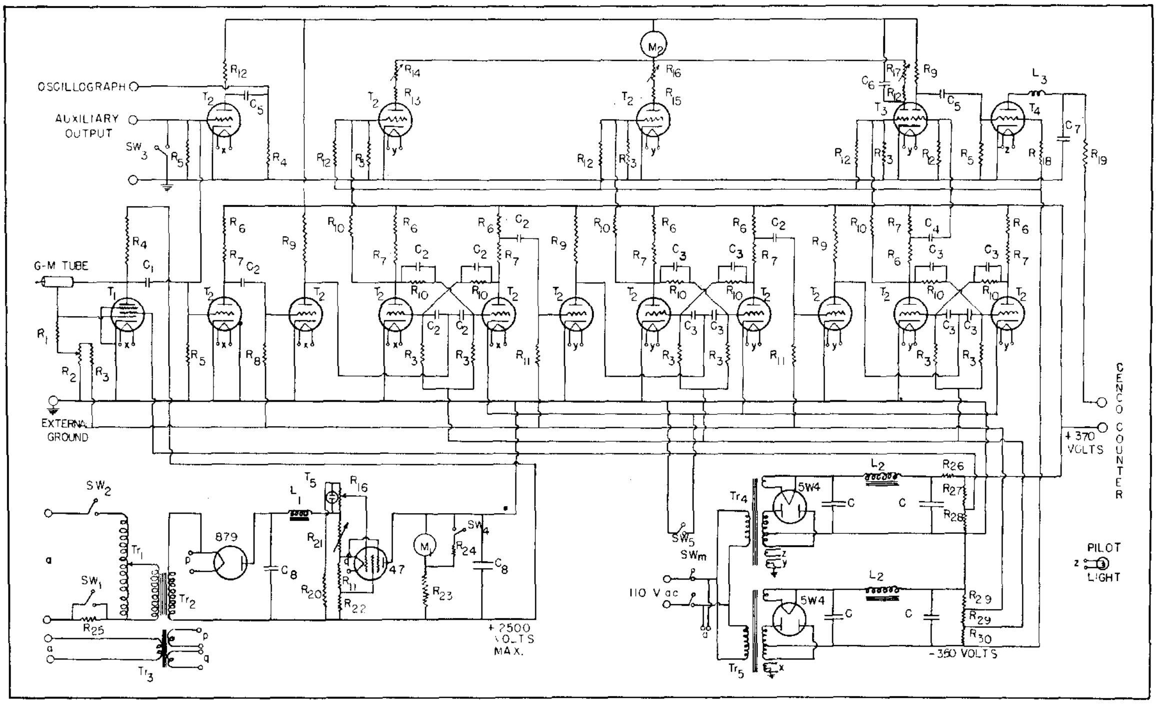

Table of circuit constants

R_1 = 10 to 20 megohms, 1 watt
R_2 = 50,000 ohm I.R.C. potentiometer
R_3 = 100,000 1 watt
R_4 = 1,000,000 2 watt
R_5 = 200,000 1 watt
R_6 = 30,000 2 watt
R_7 = 20,000 2 watt
R_8 = 20,000 1 watt
R_9 = 100,000 2 watt
R_{10} = 400,000 1 watt
R_{11} = 50,000 1 watt
R_{12} = 500,000 1 watt
R_{13} = 2,000,000 1 watt
R_{14} = 2,000,000 I.R.C. pot.
R_{15} = 1,000,000 1 watt
R_{16} = 1,000,000 I.R.C. pot.
R_{17} = 500,000 I.R.C. pot.
R_{18} = 300,000 1 watt
R_{19} = 7500 10 watt, w.w.
R_{20} = 2,000,000 6 watt
R_{21} = 50,000 pot., w.w.
R_{22} = 1,700,000 7 watt

R_{23} = 2,000,000 8 watt
R_{24} = 66 1 watt
R_{25} = 50 10 watt w.w.
R_{26} = 300 10 watt w.w.
R_{27} = 10,000 20 watt w.w.
R_{28} = 2000 10 watt w.w.
R_{29} = 2500 10 watt w.w.
R_{30} = 15,000 10 watt w.w.
C = 8–16 μf dry electrolytic, 450 volts
C_1 = 70 $\mu\mu f$ Sangamo mica, 5000 v
C_2 = 0.000025 μf mica, 600 v
C_3 = 0.00005 μf mica, 600 v
C_4 = 0.0001 μf mica, 600 v
C_5 = 0.0002 μf mica, 600 v
C_6 = 0.3 μf Solar "Domino," 600 v
C_7 = 0.07 μf Solar "Domino," 600 v
C_8 = 2.0 μf G.E. Pyranol, 2000 v
L_1 = 1100 henry, G.T.C. No. 117, 5 ma
L_2 = 20 henry, Stancor No. C-1410, 100 ohms
L_3 = 8 millihenry r.f. choke, 100 ohms
T_1 = type 6J7-G

T_2 = type 6C5
T_3 = type 6N7
T_4 = type 885 thyratron
T_5 = neon 115 v ¼-watt glow lamp with resistor removed
Tr_1 = General Radio Variac type 200-B
Tr_2 = 3000 volt neon sign transformer, 75 volt-ampere capacity
Tr_3 = filament transf., two 2.5-v secondaries, 7000-v insulation; General Transf. Co. No. 4012
Tr_4 = 700 volt c.t. power transf., rated at 85 ma, 2.5, 5.0, and 6.3 v heater windings; Jefferson No. 463-351
Tr_5 = 700 volt c.t. power transf., rated at 60 ma, 5.0, and 6.3 v heater windings; Jefferson No. 463-381
M_1 and M_2 = one ma Triplett No. 421 meters; M_2 has a 0–10 scale.
All resistors are I.R.C. type B metallized except where stated.

FIG. 1. Circuit diagram of the entire G-M system.

should always be employed for reasons given in a later section on interpolation. The complete system should be as flexible and versatile as possible to satisfy the requirements of a wide range of applications. Some such applications are the calibrating of single scale recorders, and the use of the system with any other recorder such as a frequency meter. Also one may wish to make use, by itself, of the recorder which is built into the system, e.g., in connection with an ionization chamber and linear amplifier. Means should also be provided for the oscillographic testing of G-M tubes in operation. The entire apparatus should be well shielded, preferably in a metal cabinet, so that operation of the apparatus next to the high frequency system of a cyclotron is possible. The use of metal shell tubes greatly aids in fulfilling the shielding requirements in such applications. The following sections give a more detailed discussion of a system which has been in use in this laboratory for several months. The particular design adopted followed the above considerations and additional features will appear below.

The Scaling Circuit

In Fig. 1 is given the *complete* circuit diagram of the *entire* system. The circuit of the vacuum-tube scaling circuit is the one previously given,[2] adapted for use as a scale-of-eight, and incorporating several simplifications, the principal ones being a reduction in the number of power supplies and a change in the method of coupling the interpolator tubes. These changes have resulted in a considerable reduction in size without impairing the performance of the outfit. On the lower right-hand side of the diagram are shown the two power supplies for furnishing power to the Neher-Harper tube and the entire recording system. The upper supply furnishes all plate and screen voltages and the lower all the control grid biases. Two power supplies are used to avoid interaction between the plate and grid circuits, and especially the control grid circuit of the Neher-Harper tube. The biggest factor causing such interaction when a single power supply is used, is, in this case, the heavy current drain of the stage operating the mechanical recorder. This scaling circuit may be designed to work satisfactorily on much lower voltages and with the scales-of-two self-biased.

The middle part of the diagram shows the scale-of-eight proper. The second and third tubes comprise a discriminator circuit[3] which, it was felt, was a desirable feature, especially if the recorder were used with an ionization chamber, linear amplifier outfit. After the discriminator come the three scales-of-two in series. Metal shell tubes are used throughout. The master power switch, SW_m, the reset switch, SW_5, and the start and stop switch, SW_3, are shown.

The scale-of-two shown has very recently been modified by Reich,[4] the principle of operation, however, remaining the same. With his modification, the two rectifying coupling tubes may be omitted provided that pentodoes are used rather than triodes as shown. Reich also reports an ingenious circuit using the same principles but employing only one tube. This circuit, however, requires coupling tubes between stages and is, according to Reich, quite critical as to adjustment. Since the saving in tubes (and other parts) is so small, it seems at present that the less critical circuit is to be preferred in nuclear work. Furthermore, this circuit requires an extra source of voltage for the control grid.

Interpolation

At the top of Fig. 1 are shown the interpolator triodes for running the interpolation meter, M_2, by the meter method of interpolation described previously.[2] An interpolator is extremely useful for several reasons. There are some experiments which require the extra accuracy obtainable with an interpolator. But of even greater importance in many cases is the fact that the interpolator shows at a glance the performance of each scale-of-two in the scaling circuit. This aids greatly in adjusting the circuit for proper operation and in trouble shooting when defective parts develop. Also one may easily keep a constant check on the performance of the counting system during an experiment whereas, otherwise, such things, for example, as an intermittent open in a condenser might fail to be detected and cause erroneous results to be obtained.

The Coupling Circuit

The Neher-Harper[5] tube, T_1, furnishes the means of quenching the G-M counter and coupling it to the scale-of-eight. Neher-Harper coupling was chosen because it is about as fast as any of the other circuits which have been proposed, while having many advantages for use in the present outfit. Continuous use of the Neher-Harper circuit for the past two years has shown it to be extremely reliable and positive in action. With fast G-M tubes, counting rates up to approximately 200,000 *random* counts a minute have been recorded by Neher and Harper and also in this laboratory using a vacuum-tube scale-of-128. The vacuum tube used must withstand the full counter voltage, but no insulation difficulties whatsoever have been encountered up to about 2400 volts when glass tubes are used and about 1500–2000 volts when metal tubes, such as the 6J7, are used. The tube draws an inappreciable plate current so that there is no current drain on the high voltage supply. This is an important feature if the high voltage supply is to

[2] H. Lifschutz and J. L. Lawson, Rev. Sci. Inst. 9, 83 (1937). The theory of operation of the scaling circuit is given in this paper.

[3] C. E. Wynn-Williams, *Reports on Progress in Physics* (1936), p. 239.

[4] H. J. Reich, Rev. Sci. Inst. 9, 222 (1938).

[5] H. V. Neher and W. W. Harper, Phys. Rev. **49**, 940 (1936).

be as small and light as possible. A very useful practical feature of the N-H circuit is that the cathode of the tube is at ground potential. This allowed the use of the *same* power supplies which furnished voltage to the recording circuits, to supply voltage to the control grid, screen grid and heater of the Neher-Harper tube as shown in Fig. 1.

The main disadvantage of the Neher-Harper circuit is the requirement of a variable control grid bias. The Neher-Pickering circuit[6] avoids this requirement, but since the cathode of the vacuum tube in this case is not at ground potential, a separate filament transformer must be used for the heater and also a separate supply for the screen grid. Self-bias for the screen grid has been found, in tests in this laboratory, to decrease the counting range. One may prefer to use the multivibrator coupling of Ruark and Brammer[7] and of Getting.[8] This coupling circuit requires two tubes but has several advantages, one of the most important of which is the constancy of its resolving time with different G-M counters. However, the multivibrator type of circuit has the disadvantage compared to the Neher types in that the quenching action depends on a.c. coupling, making possible a continuous corona discharge in the G-M tube.

The High Voltage Supply

The stabilized high voltage supply shown at the lower left of Fig. 1 is the Evans[9] type as modified by Gingrich[10] so as not to require the use of any batteries. The test switch, SW_1, cuts a 50-ohm resistor into the primary of the high voltage transformer. The output voltage is controlled by the Variac and the potentiometer, R_{16}. At any output voltage the circuit may be quickly adjusted for stabilization against line voltage fluctuations by means of these two controls. The test switch and meter are used to tell when stabilization is reached. It has been possible to stabilize against the 50-ohm change up to 2400 volts. The range of the meter, M_1, is changed from 2000 to 3000 volts by the switch, SW_4.

The high voltage supply was designed to furnish up to 2500 volts for use with G-M counters at atmospheric pressure. For most work 2000 volts or less is sufficient. A 2000-volt neon sign transformer may thus be used. To get the maximum voltage and best regulation with a neon sign transformer, the magnetic shunt should be removed and in some cases the primary and secondary windings moved closer together. For this reason it is preferable to buy the transformer uncased.

The Output Stage

The high impedance Cenco counter is operated by a Dunning[11] self-stopping thyratron circuit. Extensive use of this circuit has shown it to be exceedingly reliable and positive in action. It is simple, uses only one tube and can easily be made to count 75 periodic pulses per second or more. One such circuit has been in continuous use for a period of two years without adjustment. An output stage operating a message register may also be used, but involves a great reduction in counting speed and methods for prolonging the pulse applied to the register.

Constructional Details

In Figs. 2 and 3 are shown photographs of the apparatus indicating the panel layout and placement of parts on the chassis. In Fig. 2 the meter on the left reads the counter voltage while that on the right is the interpolation meter. The fluted knob on the left controls R_{16} and that on the right the Variac. The Neher-Harper bias is controlled by the center knob and dial, while the Neher-Harper tube itself is brought out with a cable in order to keep the leads to the G-M tube as short as possible. The capacity of these leads may change the observed counting rate by several hundred percent and increase the apparent threshold voltage of the counter, unless they are kept short and separate. The left-hand binding post is for an external ground, those on the right feed the Cenco counter. Finally, the switches are identified from left to right as, SW_4, SW_5, SW_3, SW_m, SW_1 and SW_2, respectively.

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[6] H. V. Neher and W. H. Pickering, Phys. Rev. **53**, 316 (1938).
[7] A. E. Ruark and F. E. Brammer, Phys. Rev. **52**, 322 (1937). Also A. E. Ruark, Phys. Rev. **53**, 316 (1938).
[8] I. A. Getting, Phys. Rev. **53**, 103 (1938).
[9] R. D. Evans, Rev. Sci. Inst. **5**, 371 (1934).
[10] N. S. Gingrich, Rev. Sci. Inst. **7**, 207 (1936).
[11] J. R. Dunning, Rev. Sci. Inst. **5**, 387 (1934).

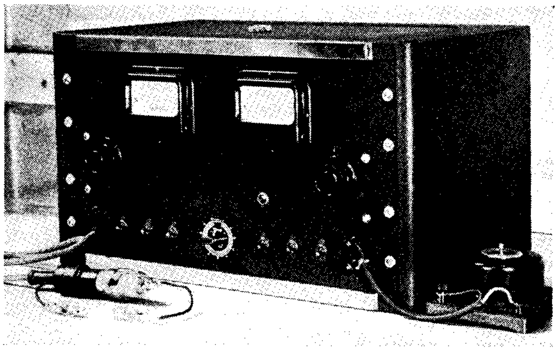

FIG. 2.

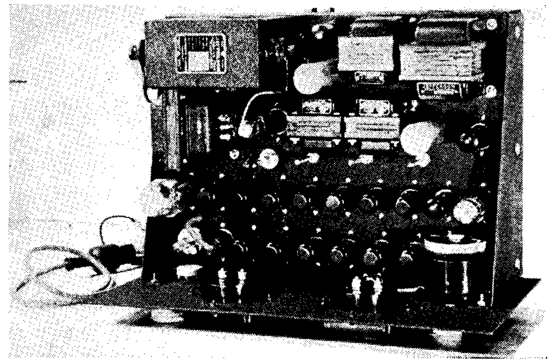

FIG. 3.

Figure 3 shows the two power supplies at the back and right of the chassis. The shafts of the three potentiometers controlling the interpolation currents may be seen in front of these power supplies. The high voltage supply is on the left of the chassis, the filter condensers and choke being underneath the sub-panel. The standard 110-volt a.c. plug is at the back and right of the chassis, and to the left of it, two pairs of output jacks may be seen. These jacks are marked *oscillograph* and *auxiliary output* on the circuit diagram, Fig. 1. The oscillograph output is furnished by a separate buffer stage which allows observation of the G-M pulses without reacting back on the circuit. Such oscillographic observation is very useful in studying and testing G-M tubes. The auxiliary output jacks allow the pulses from the Neher-Harper circuit to be fed to any other recording circuit as well as to the scale-of-eight. Similarly external pulses may be fed to the scale-of-eight through these jacks.

The high voltage supply should, of course, be well insulated. The potentiometers, R_{16} and R_{21} in this supply, are insulated from the chassis with fiber washers and also the choke, L_1. Leads are brought through the chassis through rubber grommets, and all high potential wiring is protected by spaghetti tubing. Ceramic sockets are used for the 879 and 47 tubes. The condensers, C_6 and C_7, are paper molded in Bakelite to resist heat. The condensers, C, consist of two 8-8-8 microfarad condensers of the inverted round-can type. Such condensers, the use of metal tubes, and the small power transformers and chokes required make for a small, compact system.

Additional parts not listed on Fig. 1 are as follows. The fluted control knobs are General Radio No. 637-J. Twin molded binding posts are preferable as then no precaution must be taken to prevent twisting. The cable is six conductor, each conductor being rubber insulated. The cabinet and chassis assembly is made by Par-Metal Products Corporation; cabinet No. DL-1210. The control panel is $10\frac{1}{2}'' \times 19''$ and the chassis $13'' \times 17'' \times 3''$. The chassis is enclosed on the bottom with a bottom plate supplied for the purpose.

PERFORMANCE

The resolving time of this type of circuit has been shown by direct test[2] to be 6.5×10^{-6} second for pulses of width 3.25×10^{-6} second. The maximum counting rate of the system is limited by the Cenco counter stage. This stage counts up to 75 periodically spaced pulses per second with the constants shown in Fig. 1. By running the scale-of-eight in parallel with a similar scale-of-sixteen and feeding both from a Neher-Harper circuit and G-M counter, it was found that the scale-of-eight recorded the same number of counts as the scale-of-sixteen up to counting rates of about 30,000 random counts a minute, when a Cenco counter stage which was somewhat faster than that shown in Fig. 1 was used. This agreement was partly due to the resolving time of the G-M counter circuit, which in this case was about 10^{-3} second for the particular G-M tube used. This resolving time cuts out the short intervals of the random distribution and thus allows the lower ratio scaling circuit to follow the higher ratio one up to higher counting rates than would be the case for a true Poisson distribution.[12]

[12] L. Alaoglu and N. M. Smith, Jr., Phys. Rev. **53**, 832 (1938).

For most G-M tubes we may conclude that the scale-of-eight would give the same reading as a higher ratio circuit up to counting rates of 20,000 to 30,000 random counts a minute. The losses in the scaling circuit itself are zero since its recovery time is less than that of the G-M circuit.[12] The recovery time of the G-M circuit using Neher-Harper coupling has been measured and found to depend on the particular G-M tube used.[1] These recovery times varied from 10^{-3} to 3×10^{-4} second, as compared to the minimum possible recovery times (de-ionization times) of approximately 10^{-4} second measured by Lyshede and Madsen.[13] According to these figures, scaling circuits should have a resolution time of about 10^{-4} second or less in order that they shall be able to follow the G-M circuit perfectly. Up to the above counting rates the counting losses will then be practically all in the G-M circuit, with very small losses in the Cenco counter stage.

The outfit has been used to test the beam from the Michigan cyclotron and operated satisfactorily near the unshielded, high frequency oscillator system of the cyclotron. The cost of the system, complete as shown in Fig. 1 and the photographs is approximately $110.00, the high voltage supply and cabinet accounting for about $50.00 of this amount. This does not include the Cenco counter.

Conclusion

One of the scales-of-two may be employed as a vacuum-tube frequency meter for use at very high counting rates. It would only be necessary to place a milliammeter in the plate lead or cathode lead of one of the rectifying coupling tubes, T_2, Fig. 1, between stages of scale-of-two, in order to form a complete frequency meter.[14] This could be used to correct for counting losses in the G-M circuit.[1] The interpolation meter, M_2, could easily be connected by switches to serve as the current-measuring instrument for the frequency meter as well as to serve in its present capacity. It should be strongly emphasized that, in all cases where counting losses due to the G-M circuit are corrected for by determining the resolution time of that circuit from the maximum observed counting rate,[1] sufficient amplification between the G-M circuit and the recorder must be used.[1] Otherwise the efficiency formula will not be a simple Ruark-Brammer formula and the counting losses will also be larger.[1] Sufficient amplification is achieved when further increase in gain does not materially increase the observed maximum counting rate. For this purpose more amplification may be necessary than shown in Fig. 1. This could be easily incorporated in the present apparatus.

The use of scaling circuits as frequency reducers has been suggested by Stevenson and Getting.[15] These circuits may also find a place in the accurate determination of time intervals. The Cenco counter has been used with a known constant frequency input as a fast stop watch. A scaling circuit with ratio eight or sixteen can be made to increase the range of the Cenco counter so that a standard thousand-cycle oscillator can be used. This would allow the measurement of indefinitely long time intervals with an accuracy of 10^{-3} second. For fast electronic switches suitable for such work see a paper by Reich and Toomim,[16] in which circuits of the scale-of-two type are used as switches.

In conclusion the author wishes to extend sincere thanks to Professor O. S. Duffendack for encouragement and support in this work. The support of the Horace H. Rackham Fund is also gratefully acknowledged.

[13] J. M. Lyshede and J. C. Madsen, Zeits. f. Physik **108**, 777 (1938).

[14] H. Lifschutz, Phys. Rev. **53**, 950 (1938).

[15] E. C. Stevenson and I. A. Getting, Phys. Rev. **51**, 1027 (1937).

[16] H. J. Reich and H. Toomim, Rev. Sci. Inst. **8**, 502 (1937).