A TRANSISTORIZED ANTICOINCIDENCE CIRCUIT FOR COUNTING AT LOW BACKGROUND LEVELS

By

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Introduction

Very low activities often have to be measured in health physics. The magnitude of the detectable activities depends on the efficiency of the measuring unit, on the duration of measurement and on the zero-effect (background). Only low-background units can be applied for samples having low activities. In Hungary the Research Institute for Electronics and Precision Mechanics produces two types of bell-shaped GM counters for experimental purposes, which are used in our instrument. The counting unit consists of the bell GM counter mentioned above, an anticoincidence unit designed by the authors, and a scaler.

First the detection limits in case of samples having low activities are discussed, then the principles of operation of the low background antico unit, designed by us, are described. By means of this unit it is possible to achieve about 2 PPM background, using a normal lead shield column.

Detection limits

Three different detection limits are to be considered, when measuring a sample having low activity:

1. the lowest detectable counting rate,
2. the lowest detectable activity,
3. the lowest detectable specific activity.

Let N_s be the number of counts, when measuring on the above mentioned sample for a period of t_s. The corresponding quantities in the background are N_b and t_b, respectively. Hence the counting rate for the sample is:

$$n_s = \frac{N_s}{t_s}\left[\frac{\text{pulse}}{\text{minute}}\right]. \tag{1}$$

The counting rate of the background is:

$$n_b = \frac{N_b}{t_b}\left[\frac{\text{pulse}}{\text{minute}}\right]. \tag{2}$$

The counting rate due only to the sample is:

$$n = n_s - n_b\left[\frac{\text{pulse}}{\text{minute}}\right]. \tag{3}$$

The counting rate determined in this way (3) has a certain error due to the statistical fluctuation of radioactivity. Let σ_n be the standard deviation of n. Then:

$$\sigma_n = \sqrt{\frac{n_s}{t_s} + \frac{n_b}{t_b}}. \tag{4}$$

The term $n \pm \sigma_n$ makes a better description of the counting rate due only to the sample. When measuring very low activities, the counting rate n and the standard deviation σ_n may be of the same magnitude: $n \sim \sigma_n$. In this case, since the error-limit has a value of 68.3% and the Gaussian distribution of counting rate is symmetrical, there is only a probability of 84.65% for the difference $(n - \sigma_n)$ to be positive (Fig. 1). In other words this means that the measured counting rate, different from zero, is due to the sample only with a probability of 84.65 %. The reliability limit of 68.3% is thus too small in practice. Since there are different reliability limits used in the literature, we make considerations of general validity. To each of the reliability limits a certain value of K can be attached. Multiplying σ_n by this K an interval is obtained into which the results of repeated measurements have to fall with a given probability. Some more important values of K are given in Table 1.

Table 1

Reliability intervals

Reliability interval	50%	68.3%	90%	95%	99%
Value of K	0.675	1.000	1.645	1.960	2.576

If, for example, a reliability interval of 99% ($n = 2.576 \cdot \sigma_n$) is taken into consideration, the counting rate different from zero will be determined by the sample with a probability of 99.5%.

In order to determine the lowest detectable counting rate, we should write the following equation:

$$\sigma = K \cdot \sigma_n = K\sqrt{\frac{n_s}{t_s} + \frac{n_b}{t_b}}. \tag{5}$$

Then, at the detection limit, the equation $\sigma_n = n_{\min}$ is valid, where $n_{\min}$ is the lowest detectable counting rate.

Taking the square of Eq. (5) we get:

$$n_{\min}^2 = K^2 \left(\frac{n_s}{t_s} + \frac{n_b}{t_b}\right) . \tag{6}$$

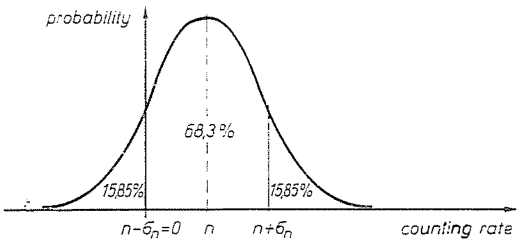

Fig. 1. Gaussian distribution of counting rate

Further the relation

$n_s = n_{\min} + n_b$ is valid too, by which Eq. (6) becomes

$$n_{\min}^2 = K^2 \left(\frac{n_{\min} + n_b}{t_s} + \frac{n_b}{t_b}\right) . \tag{7}$$

Rewriting Eq. (7) according to the decreasing powers of $n_{\min}$ a quadratic equation will be obtained.

Let us consider the positive root of this equation

$$n_{\min} = \frac{K^2}{2\,t_s} + \sqrt{\left[\frac{K^2}{2\,t_s}\right]^2 + K^2 \cdot n_b \cdot \left(\frac{1}{t_s} + \frac{1}{t_b}\right)} . \tag{8}$$

Putting the total measuring time equal to $T = t_s + t_b$, we get for the second bracket under the root-sign the following form:

$$\frac{1}{t_s} + \frac{1}{t_b} = \frac{t_s + t_b}{t_s \cdot t_b} = \frac{T}{t_s \cdot t_b} . \tag{9}$$

The monomial $K^2/2\,t_s$ factored out, Eq. (8) becomes:

$$n_{\min} = \frac{K^2}{2\,t_s} \left(1 + \sqrt{1 + \frac{4\,n_b}{K^2} \cdot \frac{t_s}{t_b} \cdot T}\right) . \tag{10}$$

If the activity of sample and background differ only slightly, it is usual to choose the measuring time of sample and background for the same value ($t_s = t_b$). Taking this fact into account in Eq. (10), we get:

$$n_{\min} = \frac{K^2}{T}\left(1 + \sqrt{1 + \frac{4\,n_b}{K^2}\cdot T}\right). \tag{11}$$

If we consider the 99% reliability limit mentioned earlier, then $K = 2.576$ and Eq. (11) becomes:

$$n_{\min} = \frac{6.635}{T}\left(1 + \sqrt{1 + 0.603\cdot n_b\cdot T}\right). \tag{12}$$

On the basis of Eq. (12) the lowest detectable activity can be calculated. Let η be the efficiency of the measuring unit, then the lowest detectable activity is:

$$A_{\min} = \frac{6.635}{\eta\cdot T}\left(1 + \sqrt{1 + 0.603\cdot n_b\cdot T}\right). \tag{13}$$

Expressing the total measuring time T in minutes and the background n_b in [pulse/minute], the *lowest detectable activity* in [pCi] is:

$$A_{\min} = \frac{2.934}{\eta\cdot T}\left(1 + \sqrt{1 + 0.603\cdot n_b\cdot T}\right)\,[pCi]. \tag{14}$$

In many cases the specific activity of a sample of mass m has to be determined. Putting the mass in [g], the *lowest* detectable specific activity is:

$$A_{\min}^{sp} = \frac{2.934}{m\cdot\eta\cdot T}\left(1 + \sqrt{1 + 0.603\,n_b T_b}\right)\left[\frac{pCi}{g}\right]. \tag{15}$$

Regarding the relations deduced above, it can be said: the better the efficiency of the measuring unit and the longer the total time of observation and the lower the background, the lower activities can be determined by the particular instruments.

Operation and layout of low-background counter

According to the experience, the background of any unit can be reduced by shielding only to a certain value. In the case of widely used end-window GM counter tubes this value is 5—6 pulse/minute at the best. If a unit of lower background is required, other solutions are to be applied. The block diagram of one of the most generally used solutions is shown in Fig. 2. The activity-measuring unit consists of two GM detectors, an anticoincidence stage and a scaler. The two GM tubes have been made in the Research Institute for Electronics and Precision Mechanics. The external bell GM tube (Type EFKI-1714)

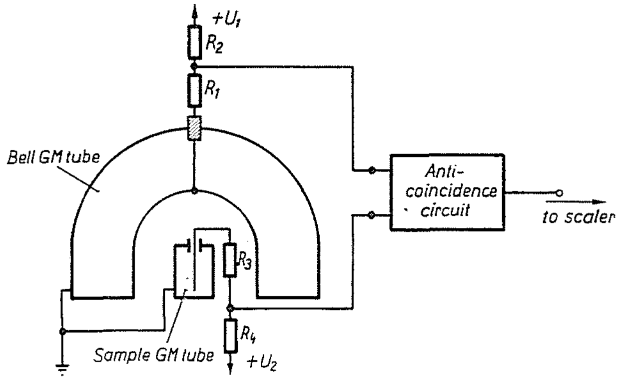

Fig. 2. Block diagram of measuring unit

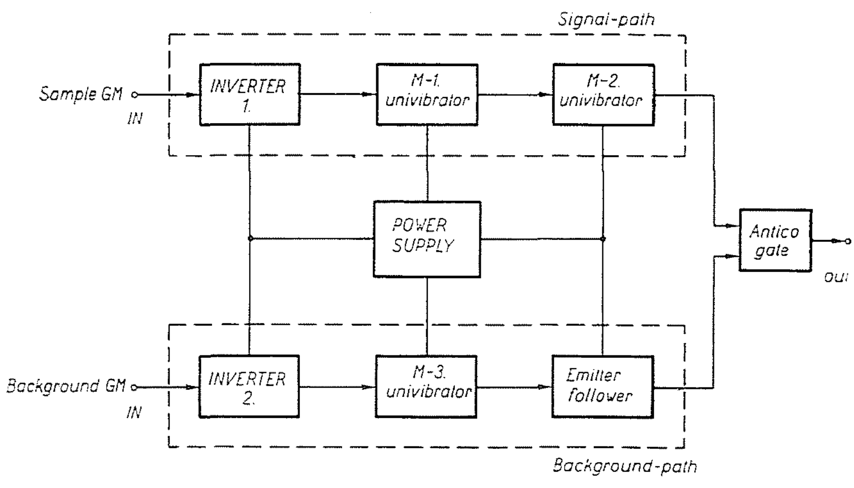

Fig. 3. Block diagram of the anticoincidence circuit

covers the internal sample GM tube, which has a 1.5 mg/cm^2 thick end-window (Type EFKI-1514), at a 2 π solid angle. They are both placed in a commercially available shield (Type Gamma, System KFKI). Each of the detectors is connected to the inputs of the antico unit. The output is connected to a scaler (Type Orion-EMG-1872). The block diagram of the antico unit is shown in Fig. 3.

In respect of operation the block diagram can be divided into four parts: signal-path, background-path, antico-gate, power-supply. The detailed block diagram of the anticoincidence unit is shown in Fig. 4.

On the inputs of the signal-path as well as on the background-path there are inverters (transistors T_1 and T_6), which convert the GM-pulses into pulses

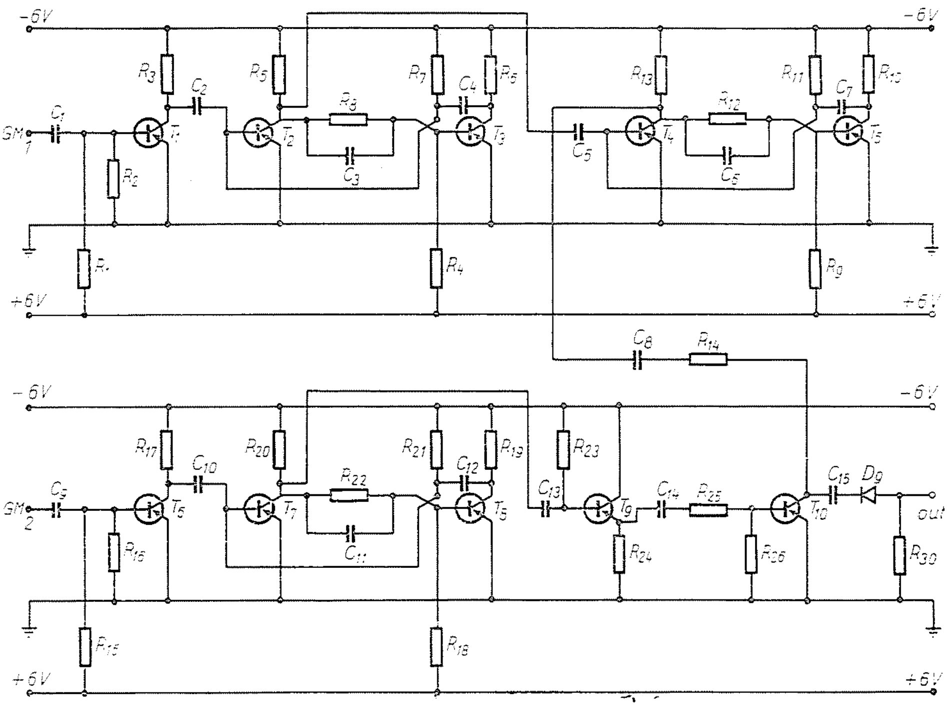

Fig. 4. Principal scheme of the anticoincidence unit

suitable for driving the univibrators M-1 and M-3. Regarding rise-time, width, and amplitude of these GM-pulses it becomes evident that these pulses are not appropriate to trigger the univibrators supplied by + 6 V and −6 V, respectively. The short rise-time of inverter pulses warrants for triggering the univibrators (Figs 7 and 8) with a delay as short as possible.

Let us have a look at the *signal-path*. The pulses of the inverter are delayed by univibrator M-1 consisting of transistors T_2 and T_3. For the resistor R_7 and capacitor C_4, which determine the width of quasi-stable state, such values have been chosen which give a delay of 60 μsec. The output pulse of inverter I_1 produces a square-pulse of positive polarity at the collector of T_3 and another one of negative polarity at the collector of T_2 (Fig. 9 and Fig. 10). The square-pulse of negative polarity is fed to an RC differential unit, where the capacity

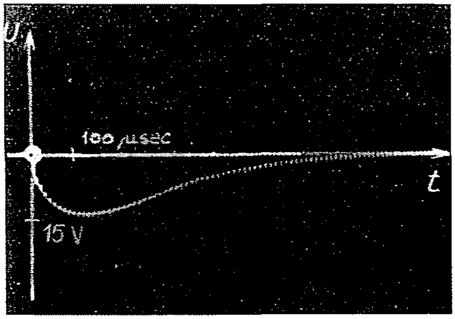

Fig. 5. Pulse of sample GM tube

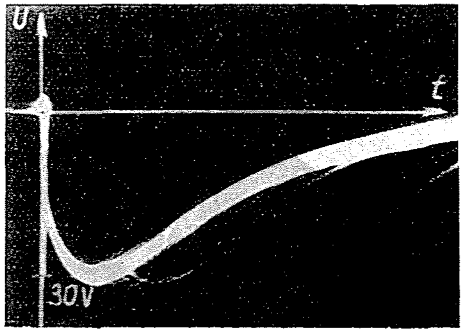

Fig. 6. Pulse of bell GM tube

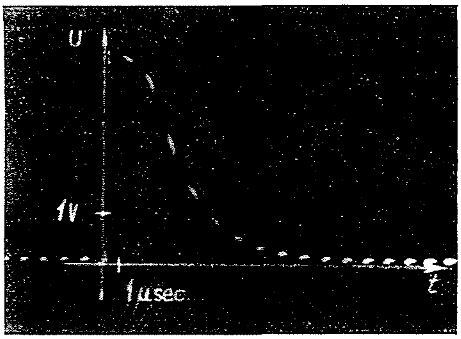

Fig. 7. Pulse form of inverter I_1

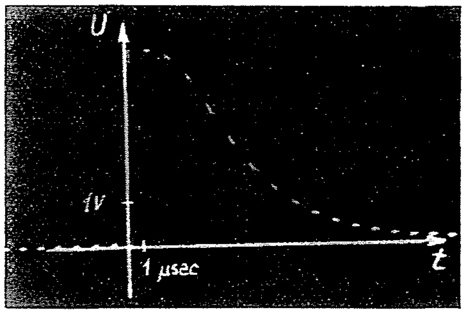

Fig. 8. Pulse form of inverter I_2

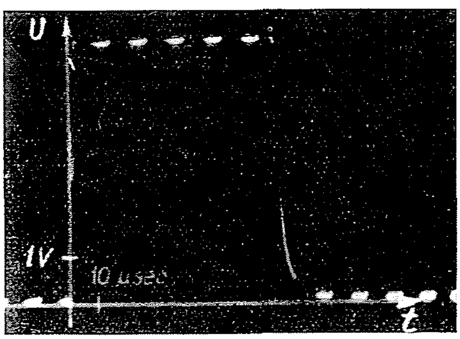

Fig. 9. Form of pulses at collector of T_3

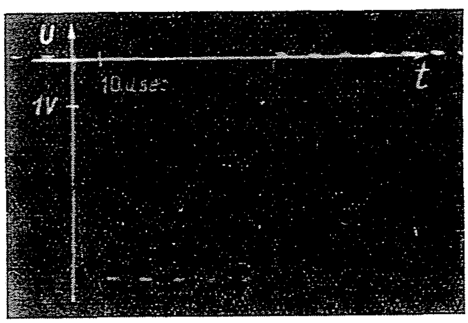

Fig. 10. Form of pulses at collector of T_2

is represented by capacitor C_5 and the resistance by the input-resistance of univibrator M-2. The univibrator M-2 is triggered then by the positive pulse of the RC differential unit. This pulse is shifted by 60 μsec compared to the nega-

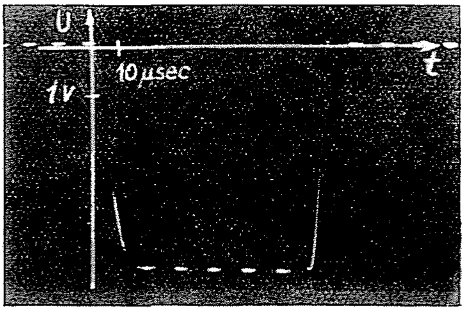

Fig. 11. Form of pulses at collector of T_4

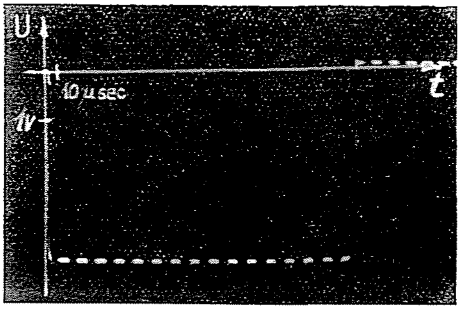

Fig. 12. Form of pulses at collector of T_7

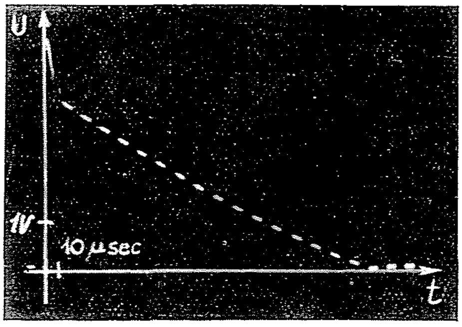

Fig. 13. Voltage variation at the base of T_7 during quasi-stable state

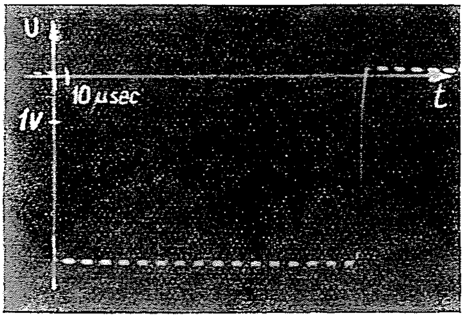

Fig. 14. Form of pulses at the emitter of T_9

tive one. The univibrator M-2 consisting of T_4 and T_5 produces that pulse of negative polarity, which will be then led up to the anticoincidence gate (Fig. 11).

Let us take now the *background-path* into account. The pulse of the bell GM tube produces, at the output of inverter I_2, a pulse as already shown in Fig. 8. The univibrator M-3 consisting of transistors T_7 and T_8 is then triggered by this pulse and gives a rectangular pulse of negative polarity at the collector of transistor T_7 (Fig. 12). The output pulse of positive polarity of inverter I_2 is connected to the base of transistor T_7, because the univibrator is adjusted in such a way that in the ground state T_7 conducts ($U_c = -0.1$ V) and T_8 cuts off ($U_c = -6$ V) (see Fig. 13). From the two pulses of the univibrator M-3 we use only the one with negative polarity, which is then led through capacitor

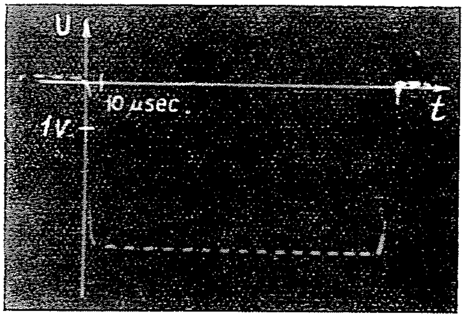

Fig. 15. Form of prohibiting pulses at the base of T_{10}

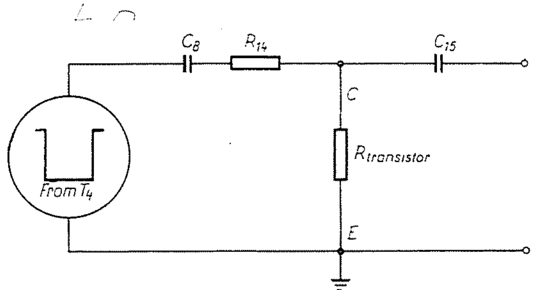

Fig. 16. Equivalent circuit of anticoincidence gate

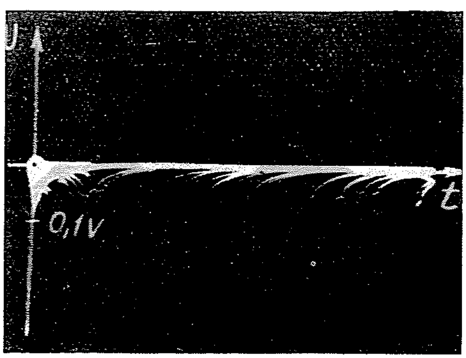

Fig. 17. Noise at the collector of T_{10}

C_{13} of sufficiently high value to an emitter-follower consisting of transistor T_9. This unit shows a great input resistance to univibrator M-3 and a small output resistance towards transistor T_{10}, respectively, thus it works for impedance-matching. This is necessary because of the small input resistance of the antico gate consisting of T_{10}. Consequently in case of direct coupling the pulse of T_7

would be attenuated so much that the remaining small amplitude would be unable to ensure the function of prohibiting.

The *antico gate* is formed by T_{10}, on the collector of which the signal-path and on its base the background-path are connected. Four distinct cases have to be discussed concerning the operation of the antico gate:

a) If there are no pulses either on the signal-path or on the background-path, there will be no pulses at the output of the antico gate. (Trivial case.)

b) Let us suppose that only through the background-path is a pulse transmitted to the base of T_{10} (Fig. 15). There will be no pulse at the collector of T_{10}, because the transistor in grounded-emitter arrangement has no power supply. This becomes evident if we analyze the diagram, since the collector of T_{10} is not in galvanic coupling with that of T_4 (capacitor C_8 represents an infinitely high resistance to *dc*). Thus it is in vain that the flow of majority-charge carriers through the emitter-base junctions starts under the influence of the pulse arriving at the base, the collector does not attain any definite potential as compared to the base and the charge-carriers will not produce any current in the collector circuit.

c) Let us suppose now that there is a pulse forwarded only on the signal-path. This one comes through the line $C_8 - R_{14} - C_{15}$ but a little attenuated by the divider $R_{14} - R_{trans}$ (Fig. 16).

d) Now, at last, it should be supposed that there is a pulse on the signal-path as well as on the background-path. As long as there is a background-pulse at the input of the antico gate, no output-pulse will appear. To make this clear let us have a look once again at Fig. 16. In the case of a background-pulse of negative polarity on the base of T_{10}, the output resistance of the transistor will fall to zero at best ($R_{tr} = 0$). For this reason, due to the shunting effect of R_{tr} the amplitude of the pulse arriving through the line $C_8 - R_{14} - C_{15}$ will also fall to zero. In reality the output resistance of T_{10} will not fall to zero exactly, and the amplitude of the pulse will not be zero either, but a finite value — in our case about 0.1 V (Fig. 17). These pulses may start the scaler. To avoid this, there is a diode limiting circuit working at the output of the antico gate (R_{30}, D_9). The diode OA 1180 represents different internal resistances dependent upon the influence of pulses of different amplitude. R_{diode} is equal to 3 . . 400 Ohms for disturbing pulses of 0.1 V, while 2 . . 4 Ohms for useful pulses of 4—4.5 V. For the resistance R_{30} such a resistor has been chosen, which gives an appropriately great value to $R_{30}/R_{diode} + R_{30}$ for disturbing pulses, while a small one for useful pulses.

Let us see the operation of our unit with two GM tubes connected to its inputs (Fig. 18). If a particle of cosmic origin is detected by the bell GM tube as well as by the sample GM tube, a pulse of 60 μsec length will come to the antico gate on the signal-path and another one of 150 μsec length on the background-path. The pulse on the signal-path is delayed by 60 μsec as compared to the pulse of 150 μsec length on the background-path. This guarantees the proper prohibiting action of the pulse on the background-path against the pulse originating from the sample GM tube. However, not all the background-pulses can be eliminated, for it is also possible that a particle of cosmic origin is de-

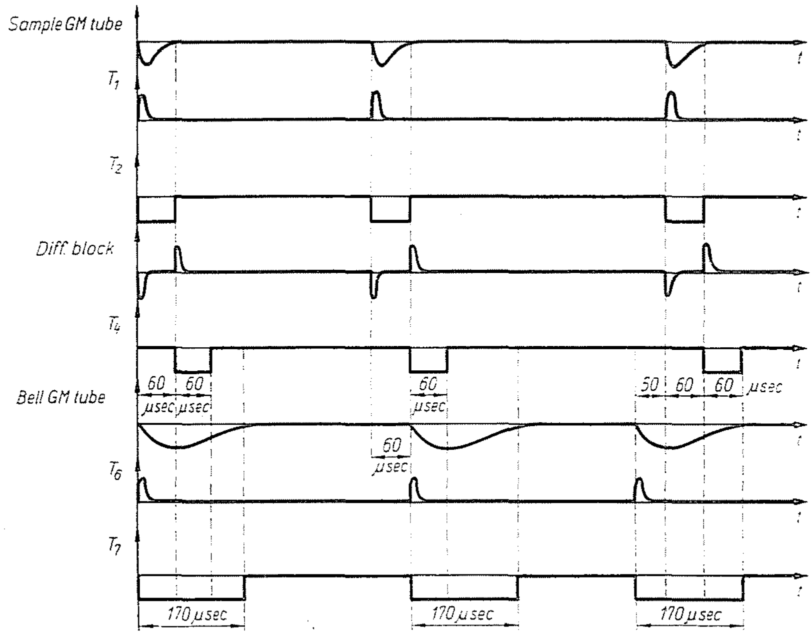

Fig. 18. Timing diagram of anticoincidence circuit

tected only by the sample GM tube, and not by the other one. This pulse wil not be hindered in reaching the scaler.

If a beta-source is placed under the end-window sample GM tube, the particles will be detected only by this tube, for the thick chrome-iron wall of the bell GM tube absorbs the beta particles almost completely. Pulses originating from the internal sample GM tube are transmitted unhindered to the scaler through the antico gate. The pulses of the bell GM tube, however, do not reach the scaler for reasons discussed previously.

At last we measured the background rates at various shielding arrangements. The results are shown in Table 2.

Regarding the application of the instrument the following remarks are to be made:

1) Both mains and battery voltage sources can be applied as power supplies. In our case the secondary coil of a small transformer was wound symmetrically, in a way that $\pm$ 6 V *dc* was obtained after rectification by a Graetz circuit. Two batteries of $+$ 6 V *dc* can also be used as supplies for the

Table 2

Background rates in different shielding arrangements

Arrangement	Sample GM tube	Bell GM tube
No shielding	15 ... 18 PPM	215 ... 230 PPM
Under shield	4.5 ... 5.5 PPM	72 ... 80 PPM
With anticoincidence unit and no shielding	5 ... 7 PPM	
With anticoincidence unit and under shield	1.8 ... 2 PPM	

instrument. In both cases it is advisable to stabilize the voltages, e.g. by Zener-diodes.

2) Samples of greater beta-activity can also be measured by this instrument in the usual way, for the background rate of the bell GM tube is only 230 PPM (Table 2). The total period of prohibition within a minute caused by the background pulses amounts to $230 \cdot 150\ \mu\text{sec} = 0.036$ sec. The counting losses due to this period are negligible. For samples of greater beta-activity, however, it is unnecessary to apply low background level counters, because the ratio pulse/background is sufficiently great in this case. The accuracy of measurement will not be affected.

3) By improving the shielding further decreases of the background can be achieved. In the literature there are such shielding arrangements reported (e.g. lead + cadmium + limestone in thickness of the order of metres), where background rates less than 0.8 PPM can be obtained. To set up a shielding of this kind, however, considerable financial investments and a personnel of appropriate number are required.

4) In order to characterize roughly the performance of our instrument, we calculated the lowest detectable activity, taking into account the following parameters: total time of measurement $T = 2$ h $= 120$ min, $n_b = 2.1$ PPM and the efficiency of detection: $\eta = 10\%$. By Eq. (14):

$$A_{\min} = \frac{29.34}{0.1 \cdot 220} \cdot \left(1 + \sqrt{1 + 0.603 \cdot 2.1 \cdot 120}\right) = 3.25\, pCi,$$

thus, an activity of 3 pCi can be determined practically with a probability of 100%.

5) The advantage of the instruments, as compared to the vacuum tube types, is the cheap production (the 10 transistors are the essential expenditure) and the fact that it does not take up much room. Furthermore no modifications of shield and scaler are necessary as the dimensions of the detector are small.

Summary

Very low activities can be measured by means of low background level counters. The first part of the present paper deals with the detection limits, in the second part the operation and layout of the circuit made by authors are discussed. Details are given on the principle of operation of the transistorized anticoincidence unit, and the statements are illustrated on oscilloscope photographs. By applying the circuit, about 2 PPM background can be achieved. No mechanical or electrical modification of the scaler and lead column shield connected to our circuit are required.

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