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Energy dependence of the positon asymmetry in muon decay

A.I.Muchin, E.B.Ozerov, B.Pontecorvo

Summary

The energy dependence of the asymmetry of positons produced by polarized muon decay is investigated with a scintillation counter technique greatly suppressing the detection of bremsstrahlung radiation. The investigation was carried out at electron energies above 20 Mev. It was found that such energy dependence agrees quantitatively with that predicted by the two-component neutrino theory.

The experiments show that the polarization of the muon beam used is equal to 0.8I±0.II.

Introduction

The parity non-conservation hypothesis[I)] naturally leads[2)] to one possibility, the so-called two-component or longitudinal neutrino theory. The attractive simplicity of such theory makes it desirable to look for experimental evidence confirming or rejecting the longitudinal neutrino hypothesis.

The investigation at different angles of the spectrum of electrons emitted in the decay of polarized muons is one of the aspect which can be analyzed from the above point of view. It is necessary, however, to underline that while such an investigation can reject the two-component theory, it cannot finally confirm it. In other words, a four-component neutrino theory with a suitable set of coupling constants[3)] can predict a spectrum of the same form as that which is definitely given by the two-component neutrino theory, namely

$$f(\mathcal{E},\theta) = 2\mathcal{E}^2\left\{(3-2\mathcal{E}) + (2\mathcal{E}-1)\lambda\cos\theta\right\} \qquad (I)$$

Here $f(\mathcal{E},\theta)$ is the electron energy distribution function, θ is the angle between the electron momentum and the muon spin, $\mathcal{E}$ is the ratio of the electron energy to its maximum possible value, and λ is a parameter dependant on coupling constants.

Parity non-conservation in π-μ-e-decay was first observed in the classical experiments of Garwin, Lederman and Weinrich[4] who proved that muon beams originating from a synchrocyclotron inner target are considerably polarized and that the angular distribution of electrons in μ-e-decay has the form $1+a\cos\theta$. It follows from above that the two-component neutrino theory predicts a definite dependence of the coefficient a on electron energy.

The energy dependence of the coefficient a found in the very first Columbia paper[4] turned out to be weaker than it was required by (I). In this investigation the electron energy was evaluated by determining the transmission of electrons through a graphite filter. Taking into account that the counter arrangement used in [4] was relatively sensitive to the bremsstrahlung radiation of electrons[5], we started an experiment in which detection of such a radiation was greatly suppressed by the technique employed.

As it will be shown further, the results of our measurments, in which a good angular resolution was used in addition to strong suppression of bremsstrahlung radiation detection, make it possible to check quantitatively formula (I) in the electron energy region above 20 Mev.

After our experiment was started there appeared another paper of the Columbia group[6] in which the observed energy dependence of the electron asymmetry in $\mu-e$- decay is closer to that predicted by (I). Qualitative agreement with formula (I) - that is, an asymmetry increase with electron energy - was obtained also in recent investigations in which photoplate[7] and propan bubble chamber[8] techniques were used. The accuracy, however, was considerably lower than it could be obtained by electronics methods.

Experimental arrangement

A beam of positive pions with 80 Mev energy produced on the synchrocyclotron inner target was used in the experiment. While passing through the fringing magnetic field of the accelerator the beam is analized and focused. Before passing through four meter concrete wall, the beam is analyzed once more by a magnet and comes into the experimental hall through a collimator. The intensity of the beam is not very high.(IOO cm^{-2} sec^{-I}); however, the good energy homogeneity permits to resolve stopped muons and stopped pions and therefore makes it more suitable for muon work than other more intensive beams available at our Laboratory.

The experimental arrangement used is shown in Fig.I. Directly in front of the monitor counters I and 2 there was placed a berillium filter with a thickness required to stop pions in the graphite target. This was necessary in calibration experiments. While investigating the asymmetry it was required that muons were stopped in the graphite target and for such purpose an additional polyethylene filter IO cm thick was placed between counters I and 2.

When measuring the energy dependence of the electron asymmetry in $\mu-e$ - decay by the method of filter absorption there arise two difficulties:

a) distortion of the spectrum of electrons passing through the filter due to multiple scattering and bremsstrahlung radiation;

b) detection of electrons having an energy less than that nominally required by filter thickness due to the registration of their (relatively penetrating) bremsstrahlung radiation.

Point (a) is discussed in the next paragraph.

As for the point (b), in order to reduce the probability of electron detection through their bremsstrahlung radiation, in our experimental arrangement for counting decay electrons the use was made of a telescope consisting of a great number of scintillation counters. The minimum threshold for electron detection in this telescope (3,4,5,6,7 in Fig.I) was rather high and, including half of the graphite target thickness, was equivalent to 9.7 g/cm^2 of polyethylene. Changes in the electron threshold detection were made by means of polyethylene filters placed between counters.

To obtain an angular resolution of the detection system better than in [4], a small value of the vertical magnetic field acting upon the muon spin was used. In the course of the whole experiment such field was constant and equal to $4.4 \pm 0.I$ oe all over the target volume[+]. The graphite target 2cm XI4cm XI4 cm was fixed in the center of a magnet shield consisting of two iron cylinders placed one above another with a gap of II cm. Such a shield, destroying the horizontal components of the magnetic field present in the hall,

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+) The authors express their gratitude to D.P.Vasilevskaja for measurements of the magnetic field values inside the magnetic shield.

provided at the same time an homogeneous vertical magnetic field of the intensity indicated above in the region where the target was located.

The block-diagram of the electronic equipment is shown in Fig.2. An impulse from the monitor coincidence circuit (I,2) passing through the anticoincidence circuit (I,2)-3 triggered the time selection circuit. The time selection system for decay electrons was a 3-channel one; gate widths were I μsec long each. The delayed electron impulses detected by the fivefold coincidence circuit were fed into the gating systems and registered by numerators.

At minimum detection threshold and in the geometry indicated in Fig.I the intensity of positons from μ-e- decay was $\sim$ 30 per min. When on the beam path there was placed only the berillium filter, in order that pions get stopped in the C target, the intensity of electrons from π-μ-e-decay was $\sim$ 200 per min.

Due to the fact that the chosen magnetic field rotated the angular distribution only by 2I° per I.0 μsec (the muon precession frequency is $f = g\frac{eH}{4\pi m_\mu c}$), two sets of measurements were carried out, each at two angles symmetrical with respect to the collimator direction (and also with respect to the target): I) 52° and I80° + 52°, and 2) I28° and I80° + I28°. The target was fixed at 45° to the beam, as it is shown for the first case in Fig.I. Taking into account the rotation of the muon spin in the constant magnetic field, measurements at these four angles with three time channels made it possible to obtain the angular distribution of electrons with respect to the muon spin at I2 angles in the angular region 0° - 360°. These angles were equal to II°, 32°,6I°, 88°, II0°, I70°, I9I°, 2I2°, 24I°, 268°,290° and 350°, after corrections were made which took into account angular resolution and the exponentional form of decay within the "gate" width.

Essentially for the determination of the coefficient a we had at our disposal three pairs of points symmetrical with respect to the muon spin direction near 0° and 180°. Besides there were 6 more points pair symmetrical near 90° and 270° which were designed to check the overall symmetry of the experiment.

It should be emphasized that small possible differences in gate widths are not a serious cause of error in determining the coefficient a , as counting intensities which need to be compared were measured at different angles with the same gates.

A variable delay line (Fig.2) made it possible to vary the gate triggering time within 0 to 5.0 μsec after the time at which a meson passed through the counters (I,2). This was used for evaluating the background of random coincidences. In the experiment a 0.4 μsec delay was used throughout. The background, the main source of which were muons stopping in the magnetic shield wall and giving decay electrons, was 5-10%. It depended on the thickness of the polyethylene filter practically in the same way as did the rate of decay electrons from muons stopped in graphite.

Investigation of the absorption for electrons emitted by non-polarized muons

For the interpretation of the absorption curves of electrons emitted at different angles by polarized muons which are discussed in the next paragraph, it is necessary to know the probability $\varphi(\mathcal{E},R)$ of detecting an electron with given energy $\mathcal{E}$ passing through a nominal polyethylene filter of thickness R. In our case R means the filter thickness plus the thickness of scintillation counters and half the thickness of the graphite target.

The passage of electrons through the matter is a rather complicated phenomenon due to the multiple scattering and bremsstrahlung radiation. However, the corresponding elementary interaction laws are well known and therefore the problems of electron passage through matter are connected only with mathematical difficulties. Practically this problem can be solved both experimentally making use of a source of monokinetic electrons of different energies or by the Monte-Carlo method. We used the results of calculations by the Monte-Carlo method given in Lokanathan and Steinberger's paper[9] in order to obtain the probability that electron pass through polyethylene of different thicknesses.

To evaluate the applicability of the method an investigation was made of the absorption in polyethilene of the electrons with known spectrum produced in non-polarized muon decay. The experimentally determined curve was compared with the absorption curve calculated for this spectrum on the basis of Monte-Carlo data[9].

As is known the electron spectrum arising in non-polarized muon decay is completely determined by the Michel parameter ρ. According to experimental data (see, for instance[3]) the value of this parameter is near to that predicted by the two-component neutrino theory and therefore we used $\rho = 0.75$[+/] in our calculations.

The solid curve of Fig.3 represents the calculated dependence

$$\mathcal{N}(R) = \int_0^1 \varepsilon^2 (3-2\varepsilon)\cdot \varphi(\varepsilon, R)\, d\varepsilon .$$

The curve was normalized so that the counting rate was taken equal to unity when the threshold of the telescope (3,4,5,6,7) registering electrons was determined only by the thickness of scintillators.

+/ Radiative corrections[3] do not change the state of affairs in this problem.

In the experimental determination of the absorption curve, between counters I and 2 there was no filter, so that pions were stopped in the graphite target. The telescope for electron detection was fixed at the angle of 232° with respect to the direction of the meson beam, in the same geometry as it was used in the measurements of the μ-e-decay asymmetry. Polyethylene filters were placed between counters. The experimental points obtained are also shown in Fig.3.

As we can see from the figure, the calculated curve is in good agreement with the experimental points. This justifies the method used in the following paragraph to take into account the distortion in the spectrum of electrons passing through polyethylene filters. A noticeable discrepancy between calculated curve and experimental points is observed only when the total thickness of the filter is more than 22 g/cm^2 of polyethylene where such discrepancy is about IO per cent. The relative discrepancy between the theoretical curve and the experimental points increases with filter thickness. Thus, when the filter thickness is sufficient to stop through ionization losses 55 Mev electrons, the telescope is still registering 0.4% of the number of electrons registered without additional filters (when $R = 9.7$ g/cm^2). Thus we can conclude that the discrepancy is not due to errors in theoretical calculations but to the non-zero probability of bremsstrahlung radiation detection[5)] by the telescope. The fact that the detection probability of bremsstrahlung is quite small is due to the arrangement of counters which had been deliberately selected, namely to the large number of scintillators in the telescope.

Dependence of the asymmetry on the energy of electrons produced in μ-e decay

Fig.4 shows the experimental values of the asymmetry coefficient a, which were obtained by the least square method from angular distribution curves determined at different filter thicknesses. The indicated errors are only statistical.

As it was stated above, at a filter thickness of 21.7 g/cm^2 (the maximum thickness used) about 10% of the counting rate in the telescope registering electrons from non-polarized muons was due to bremsstrahlung radiation. This can lead to an underestimation of the asymmetry measured with this filter. However the upper limit of the correction taking into account this effect turns out to be considerably less than the statistical error indicated. It is not excluded, however, that in the investigations [4,6] where the probability of bremssrahlung detection was considerably greater, this effect might give a more pronounced asymmetry underestimate.

The solid curve given in Fig.4 represents the dependence of the asymmetry coefficient $a(R)=B\alpha(R)$ on the total filter thickness R in the telescope and was calculated from the form of the spectrum predicted by the two-component neutrino theory (formula I). The value of the constant B (which gives the scale in Fig.4) will be discussed below.

Bremsstrahlung radiation and multiple electron scattering as well as the angular telescope resolution were taken into account; the dependence given by the solid line was obtained in the following way:

$$\alpha(R)=\frac{\int_{\Delta\Omega}\int_0^1 \varepsilon^2(2\varepsilon-1)\cdot\varphi(\varepsilon,R)\cdot\cos\theta\cdot d\varepsilon\cdot d\Omega}{\Delta\Omega\cdot\int_0^1\varepsilon^2(3-2\varepsilon)\cdot\varphi(\varepsilon,R)\cdot\cos\theta\, d\varepsilon}$$

where the integration over Ω takes into account the finite angular resolution of the telescope. The reliability of the used function $\varphi(\mathcal{E},R)$ – the probability that an electron with energy $\mathcal{E}$ will be registered by the telescope when the total filter thickness is equal to R – was discussed in the previous paragraph.

The smallness of errors possible in the calculation of the solid curve given in Fig.4 can be appreciated also if a comparison of it is made with the dashed curve

$$\alpha(R) = \frac{\int_{\mathcal{E}}^{1} \mathcal{E}^2(2\mathcal{E}-1)\,d\mathcal{E}}{\int_{\mathcal{E}}^{1} \mathcal{E}^2(3-2\mathcal{E})\,d\mathcal{E}} = \frac{1}{3}\,\frac{1+\mathcal{E}+\mathcal{E}^2+3\mathcal{E}^3}{1+\mathcal{E}+\mathcal{E}^2-\mathcal{E}^3}$$

obtained for the ideal case of absence of any distortion of the spectrum of electrons passing through the filter. The discrepancy between these two curves, as it can be seen in Fig.4, is relatively small in spite of the fact that the spectrum distortion is known to be very considerable. This is so because the discrepancy reflects only the different degrees of spectrum distortion at different angles. This circumstance makes the chosen method quite suitable in our problem, i.e., the errors in the solid curve are negligible.

As it is seen the solid curve computed from the two-component neutrino theory within few per cent agrees with the experimental points in the investigated energy region above 20 Mev.

The constant B=0, 70$\pm$0.02 obtained by fitting the experimental data with the calculated curve can be expressed as $B=P(I-W_c)\lambda$, where P is the degree of polarization of the muon beam, W_c is the probability of depolarization of muons in graphite and $\lambda = \frac{g_V^* g_A + g_A^* g_V}{|g_V|^2+|g_A|^2}$ is the fundamental constant of $\mu - e$ decay in the two-component theory (formula I). The error indicated above is only statistical. The constant B and its uncertainty were found altogether from four measurements made with different filters; it was tacitly assumed that the quantitative agreement of calculated curve with experimental points (Fig.4) is sufficient to make definite conclusions about the validity of the dependence expressed by formula (I). Then it is possible automatically obtain the integral value of the asymmetry coefficient a_0 for all the electron spectra by extrapolating the solid curve to zero filter thickness. It is found that $a_0 = \frac{B}{3} = 0.233 \pm 0.007$, this value relating , of course, to the muon beam used.

Analyzing all the data on measurements of the asymmetry of electrons from $\pi^+ - \mu^+ - e^+ -$ decay in photoplates and $\mu^+ - e^+$ decay in photoemulsions and graphite Wilkinson[10] made the conclusion that the value $(1 - W_c)\lambda = 0.87 \pm 0.12$. Comparing this result with the value $B = P(1 - W_c)\lambda = 0.70 \pm 0.02$ obtained in the present investigation one may conclude that the muon beam used has the degree of polarization $P = 0.81 \pm 0.11$ that is, in all probability, it is not completely polarized.

If one compares the asymmetry coefficients a_0 in graphite for different muon beams(obtained ,true, in an analogous manner from synchrocyclotron internal targets)[6,11,12] it is seen that the differences may be not significant. This means that muon beams have similar degree of polarization independently of the energy of protons (in the interval 400-700 Mev) which generate pions on the inner target of the synchrocyclotron.

In conclusion it should be noted that so far there is no experimental indication that λ is less than one, that is, less than the value required by the Feinmann and Gell-Mann theory[13].

Conclusion

I) The energy dependence of the electron asymmetry in decay was measured by an electronic method greatly suppressing the probability of electron bremsstrahlung radiation detection.

2) The found energy dependence of the asymmetry in the investigated positon energy region > 20-Mev quantitatively (within a few per cent) agrees with the prediction of the two component neutrino theory.

3) Making the assumption that this dependency is valid also for the unanalyzed portion of the positon spectrum (energy < 20 Mev), a value of 0.233 ± 0.007 was found for the asymmetry coefficient in graphite relating to the integral spectrum.

4) The muon beam used in our experiment in all probability is not completely polarized: the degree of its polarization is $P=0.8I \pm 0.II$.

5) Beams of muons obtained from pions generated on the inner target of synchrocyclotrons have about the same degree of polarization independently of the accelerated proton energy, in the interval 400-700 Mev.

Figure captions

Fig.I. Experimental arrangement
Be – berillium filter
C – graphite target
I,2,3,4,5,6,7 – scintillation counters

Fig.2. Block-diagram of the electronics equipment
d.a. – amplifiers with distributed parameters connected with the outputs of the photomultipliers I,2,3,4,5,6,7.

I,II,III – coincidence circuits (τ =I.5 x 10^{-8}sec)

AC – anticoincidence circuit (I,2)-3

KF – cathode follower
v.d.l. – variable delay line

T_I, T_2, T_3 – triggers.

d.e. – differentiating elements

g_I, g_2, g_3 – gates.

Fig.3. Absorption curve of electrons from unpolarized muon decay. The solid curve is the calculated dependence of the electron intensity upon the polyethylene filter thickness R.

O – experimental points.
The counting rate of the telescope is taken equal to one when there are no additional filters, i.e. when its detection threshold is 9.7 g/cm^2.

Fig.4. Dependence of the asymmetry coefficient α on electron energy.

The solid curve $\alpha(R)$, with which experimental points must be compared, is calculated taking into account the efficiency of electron detection in the experimental arrangement.
R is the total filter thickness.
The dashed curve $\alpha(\mathcal{E})$ is calculated on the assumption that there is no any spectrum distortion.

Ī – experimental values of the coefficient α .

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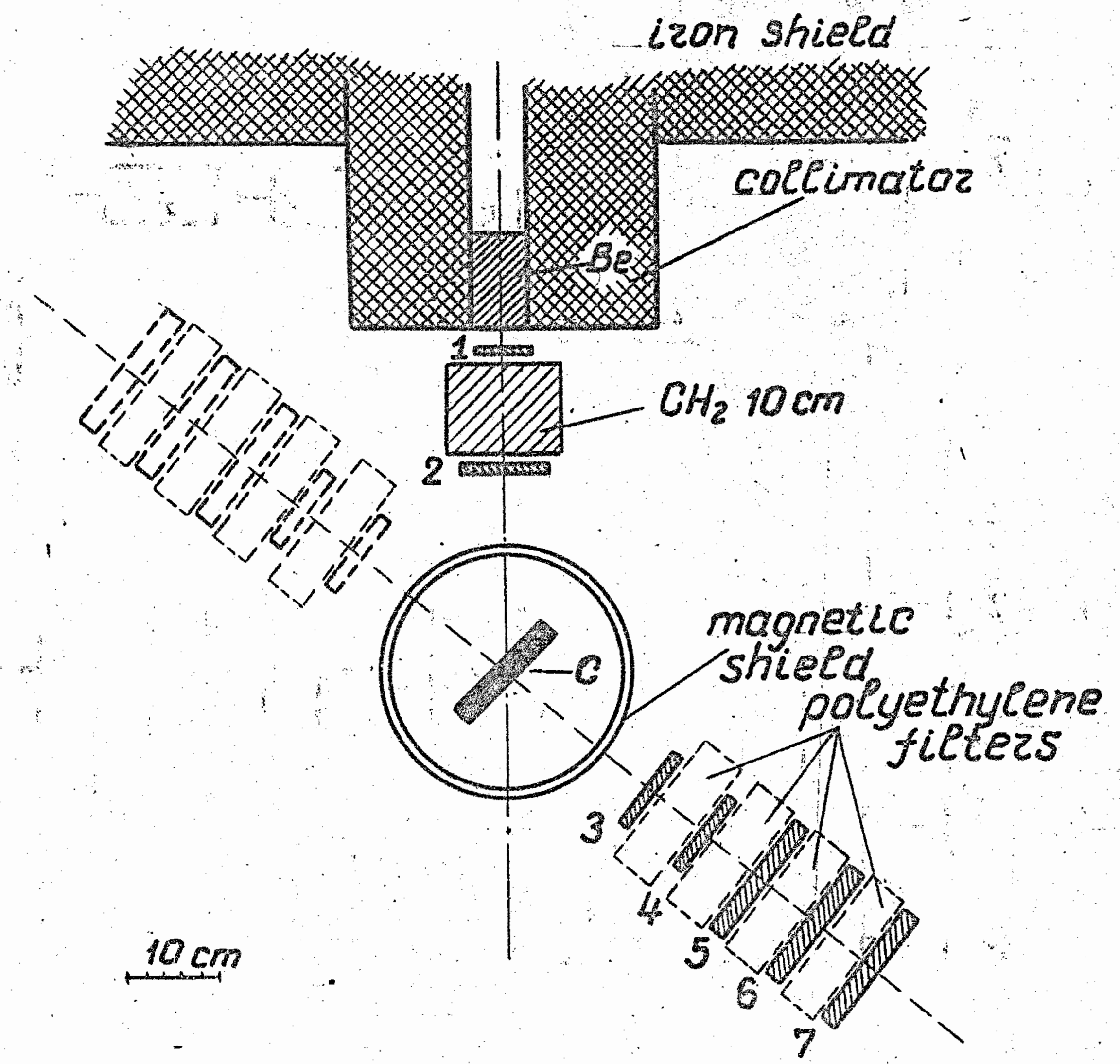
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collimator
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Fig.1

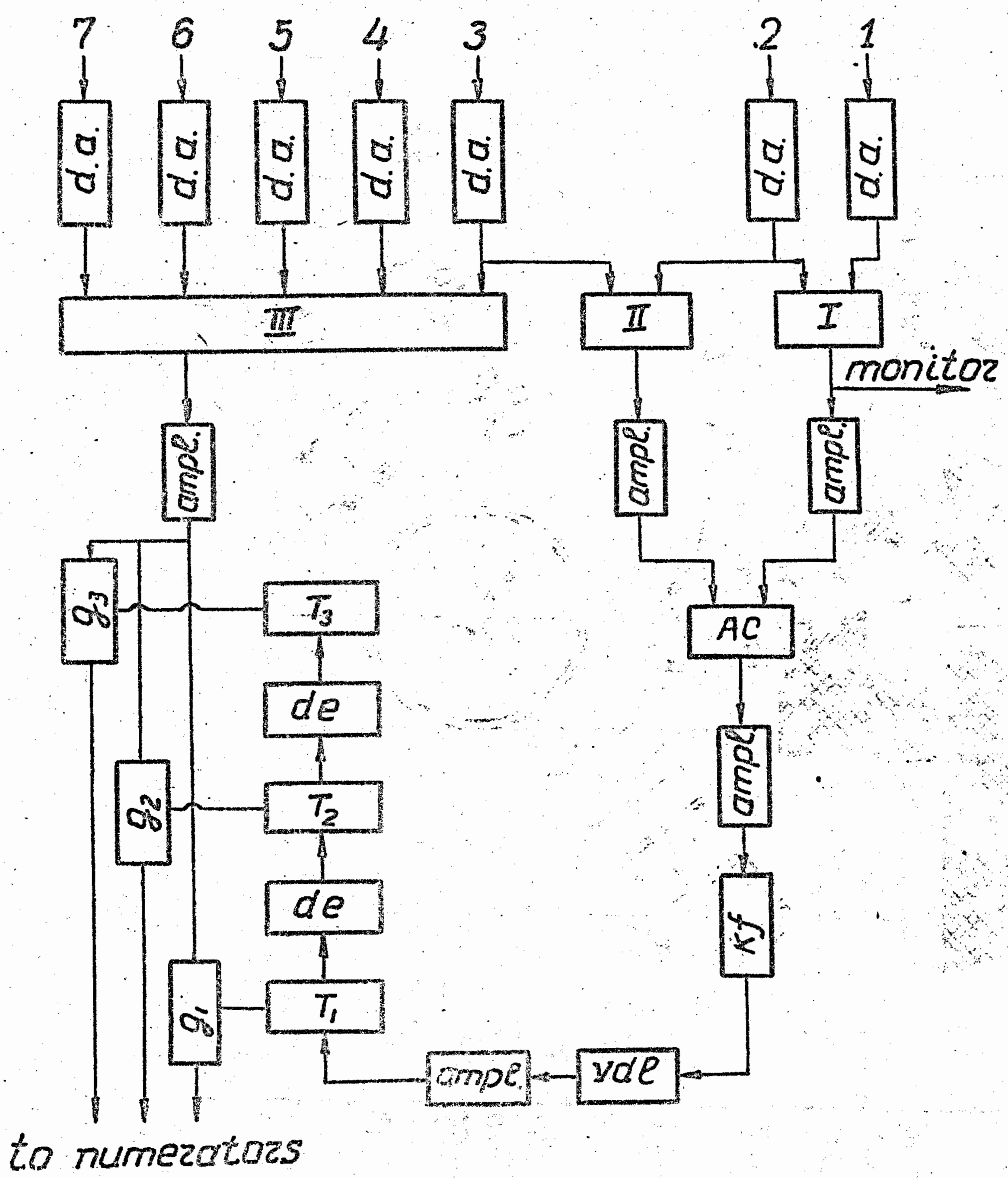
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Fig. 2

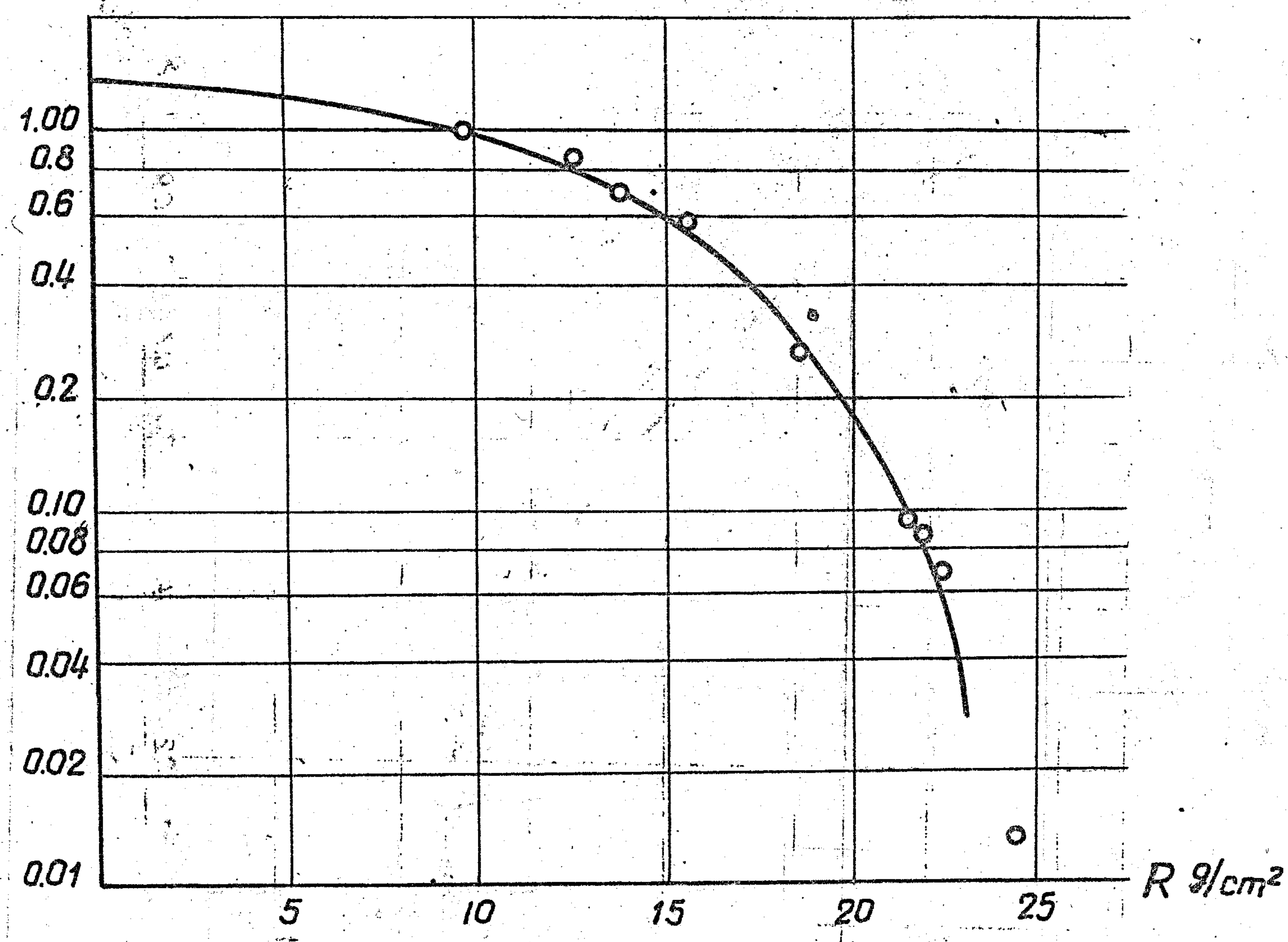

Fig.3

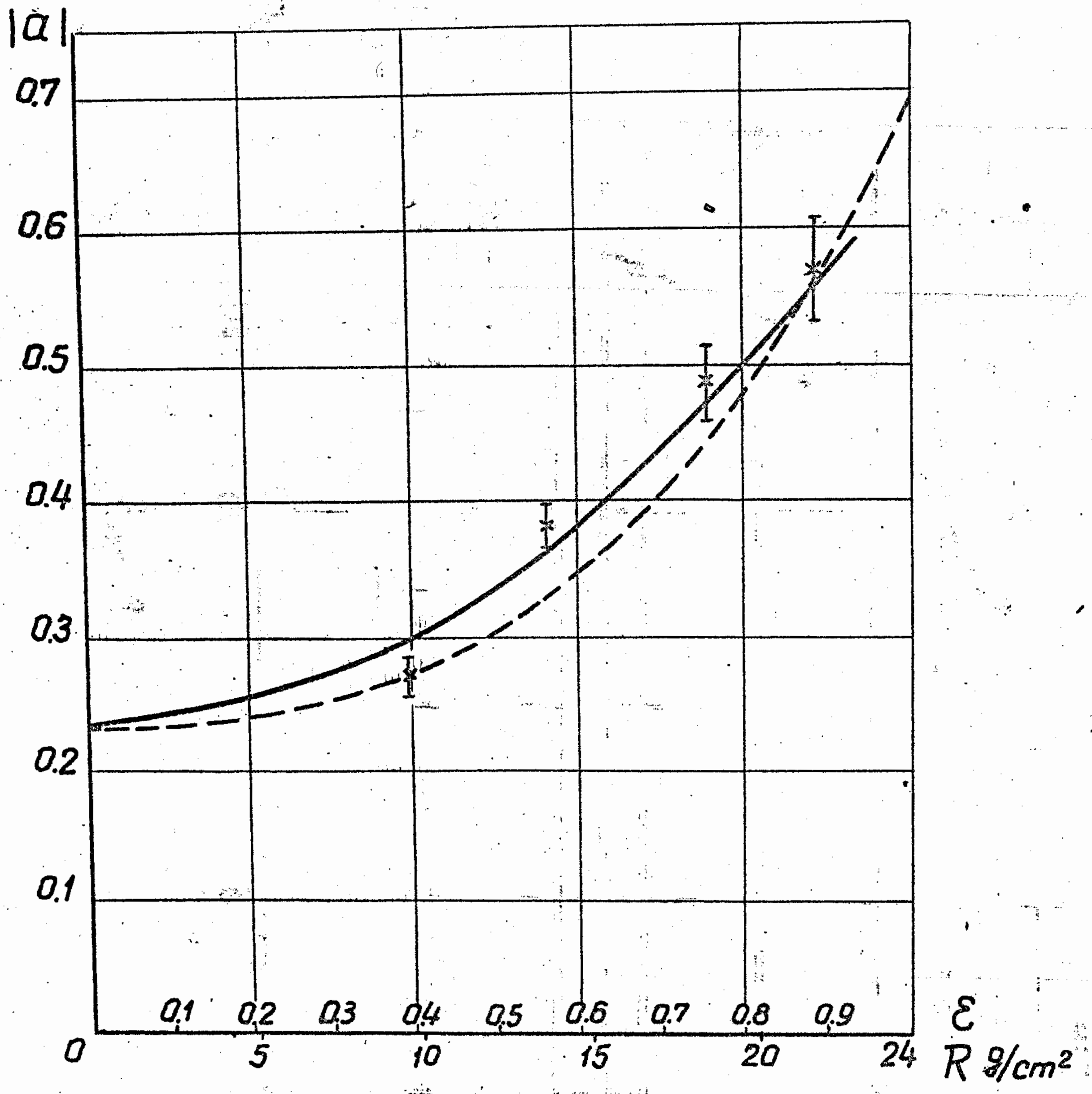

Fig. 4