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ОБЪЕДИНЕННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ

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ISOTOPIC SPIN CONSERVATION AND PION PRODUCTION

(Survey)

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I

The aim of this report is to convey in short the results of several experiments carried out recently at the Laboratory of Nuclear Problems (JINR) synchrocyclotron. These experiments pertain to different branches of nuclear physics but all of them, to a certain extent, concern various aspects of one of the most interesting modern problems - the hypothesis of isotopic spin conservation (isotopic invariance). As is known, the essence of this hypothesis comes to the assumption that the universe is built of a considerably less number of particles than it is observed in fact, that, for example, such outwardly unlike particles as proton and neutron, are only two different states of the same particle - the nucleon. To describe this circumstance the quantum-mechanical value, isotopic spin T is introduced which describes the main particle (e.g., the nucleon). The varieties of this particle (the proton and the neutron in our case) are described as various projections of isotopic spin. However, the content of the hypothesis, apparently, is not exhausted only by this. Let us consider, e.g., a system consisting of two nucleons. Isotopic spin of such a system can have two values: $T = 1$ and $T = 0$. These values are introduced quite formally, practically speaking. But as far as they are introduced, a question arises: what is the real difference between the two states which they describe ? And it turns out that interactions in these two states do not entirely resemble each other. This makes one already be on the alert: might isotopic spin be a bearer of a real physical content ? In this connection the hypothesis of isotopic invariance is studied at present from two different sides: 1) attempts are being undertaken to find out to what degree the law of isotopic spin conservation is carried out; whether it is a 'good' quantum number, and 2) it is being investigated what the difference of interactions in various isotopic spin states is.

II

The first of these questions was studied in experiments where the investigation of pion production in high energy deuteron collisions

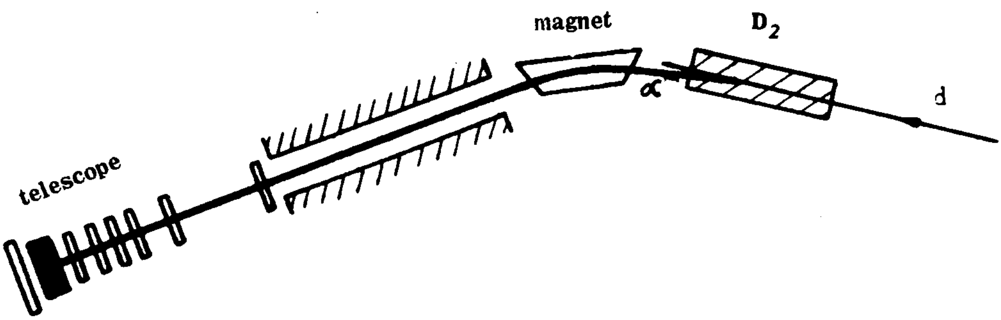
$$d + d \rightarrow \pi^{0} + \alpha \qquad (1)$$

was performed at our laboratory by Yu. Akimov, O. Savchenko and L. Soroko. The above reaction gives a unique possibility of testing the reliability of isotopic spin conservation hypothesis. As is shown by Lapidus/1/, this reaction can take place only in the case if isotopic spin is not conserved. Indeed, remembering that isotopic spins of the deuteron and α - particle are equal to zero and isotopic spin of π^{0} meson is equal to a unit, we see that process (1) corresponds to the change of isotopic spin by a unit. In order to have an opinion on isotopic nonconservation in this reaction, its probability should be compared to the probability of another reaction

$$d + d \rightarrow \gamma + \alpha \qquad (2)$$

which resembles the first one but is of electromagnetic nature. The cross section of the latter is very small ($\approx 10^{-32}$ cm^2). In this connection the investigation of processes (1) and (2) is a laborous task.

Experimental arrangement used by the authors of this paper is presented schematically in Fig. 1 (in



F i g. 1. Experimental arrangement of the reaction $d + d \rightarrow \pi^0 + \alpha$ studies.

the arbitrary scale). The experiments were carried out with a deuteron beam at an energy of 400 MeV, the intensity being 10^{11} deuterons per second. Gas deuterium pumped into a tube 1.5 m long served as a target. Particles emerging from the target were deflected by the analysing magnet and were registered by a complicated counter system. With this system it was possible 1) to registrate only particles having a definite momentum, 2) to divide particles by the time of flight (the first two counters), 3) to separate alfa-particles from deuterons and other lighter particles making use of the difference in the value of ionisation losses, 4) to registrate only those particles which have a given value of the ionisation range. The work with such a complicated technique is impossible without performing periodically repeated test and calibration experiments. The registration of He^3 nuclei from the comparatively intensive reaction $d + d \rightarrow n + He^3$ taking place in the target was one of such experiments.

Neither reaction (1) nor electromagnetic reaction (2) have been found by the authors though they have got to very small cross sections. They have obtained the following estimate of the upper limit of the cross section value of reaction (1)

$$\sigma(1) < 2\ 10^{-32}\ \text{cm}^2.$$

Thus, the degree of reaction (1) prohibition turned out to be great. In case, when isotopic spin was not conserved, the intensity of reaction (1) could be two orders higher than the given estimate. Further attempts to go deeper into the region of small ι cross sections will meet evidently with quickly rising difficulties since already in the experiments described above the counting rate was only I count per several hours.

III

The second work, I shall speak about, is dedicated to the study of the little known reaction of charged pion production in neutron-proton collisions:

$$n + p \rightarrow \pi^+ + n + n \quad \text{and} \quad n + p \rightarrow \pi^- + p + p \ . \tag{3}$$

This reaction is of interest from the point of view that when studying it one can obtain informations on the value of the cross section of pion production by nucleons in state with isotopic spin equal to zero (σ_0). It should be said that unlike another cross section (with $T = 1$)

$$\sigma_1 = \sigma^+_{pp} + \sigma^0_{pp} \ , \quad * \tag{4}$$

which is determined now rather accurately the cross section σ_0 is a value which is difficult to access. It is concerned with the fact that one has to determine σ_0 as a small difference between comparatively large cross sections and, naturally, this causes considerable errors.

The cross section σ_0 can be expressed by an arbitrary number of linear combinations of usual cross sections (only two of them are independent). Here are the most convenient of these combinations:

$$\sigma_0 = 2(\sigma^0_{pn} + 2\sigma^+_{pn}) - (\sigma^+_{pp} + \sigma^0_{pp}) \ , \tag{5a}$$

$$\sigma_0 = 6\sigma^0_{pn} + 3\sigma^0_{pp} - 3\sigma^+_{pp} \ , \tag{5b}$$

$$\sigma_0 = 3\sigma^0_{pn} + 3\sigma^+_{pn} - 3/2\,\sigma^+_{pp} \ , \tag{5c}$$

$$\sigma_0 = 6\sigma^+_{pn} - 3\sigma^0_{pp} \ . \tag{5d}$$

The first of these relations requires the knowledge of the cross sections of all the reactions of single pion production in nucleon collisions, the second and the third reactions should be used when the cross sections σ^+_{pn} ** and σ^0_{pp} , respectively, are unknown. The last relation does not include

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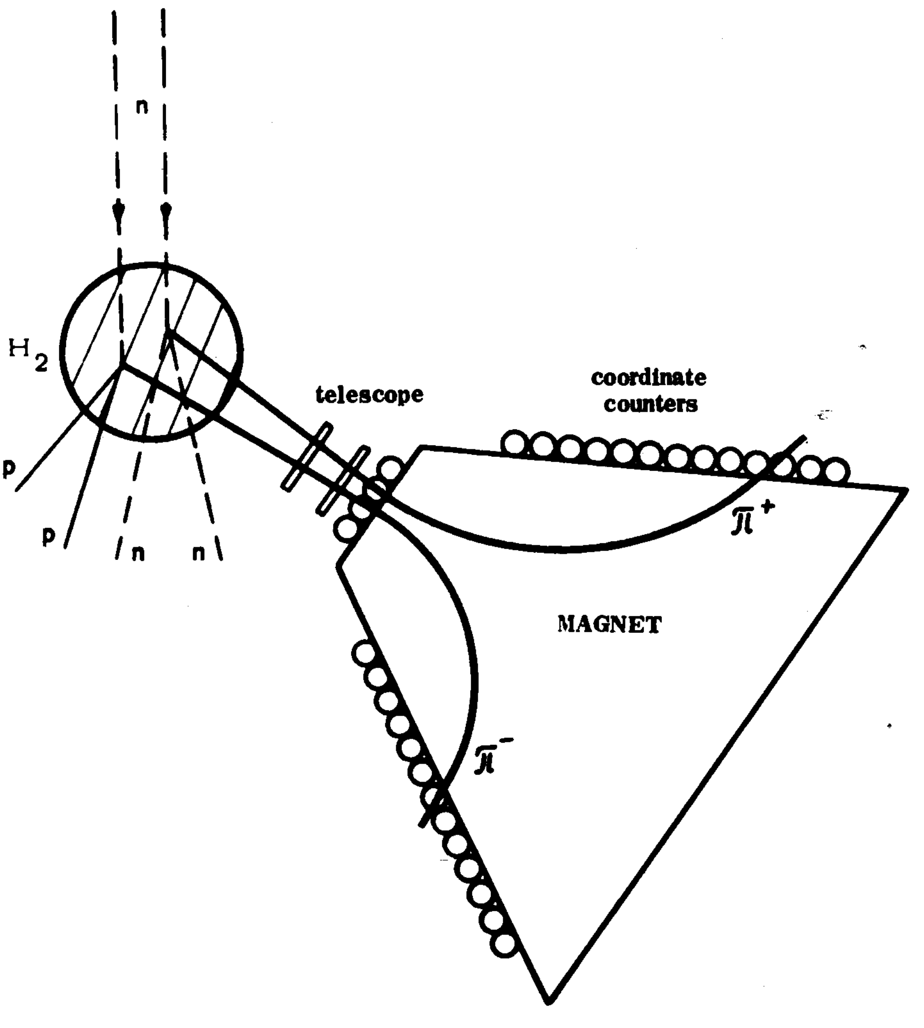
* The following notations are taken: σ^+_{pp} is the cross section of the reaction $p + p \rightarrow \pi^+ +$ nucleons, etc.

** Note that the error of the determination of the value σ_0 is especially large in this case.

the cross sections of two of the most intensive reactions: σ^{+}_{pp} and σ°_{pn} . Owing to this it profitably differs from the first two relations since it permits one, first, to determine the value of σ_0 basing on the knowledge of two cross sections only, and second, the error of such a determination is comparatively small, since cross sections forming relation (5d) are not large. Thus, simultaneous investigation of the reaction p + n → π^{+} and p + p → π° is the most convenient way of studying the process of pion production in state with isotopic spin T = 0.

Experimental investigation of reaction (3) has been carried out by V. Dzhelepov, V. Kiselev, K. Oganesyan and V. Flyagin with the neutron beam at an energy of 590 MeV. Experimental arrangement is given in Fig. 2. Charged pions produced in a liquid hydrogen target were registered with a large



F i g. 2. Magnetic spectrometer for the investigation of the reactions $n + p \to \pi^- + p + p$ and $n + p \to \pi^+ + n + n$

multichannel magnetic spectrometer which gave a possibility of studying the energy spectra of pions of both signs simultaneously. Such measurements were carried out for four angles of pion emission. The transition from one angle to another have been carried out by rotating the whole spectrometer round the target. On introducing the corrections, which are due to the electron and μ meson contamination, the authors have got the summed angular distribution of π^+ and π^- mesons in the centre of mass system of colliding nucleons to be close to isotropic (see Fig. 3) and to be well described by the polynomial

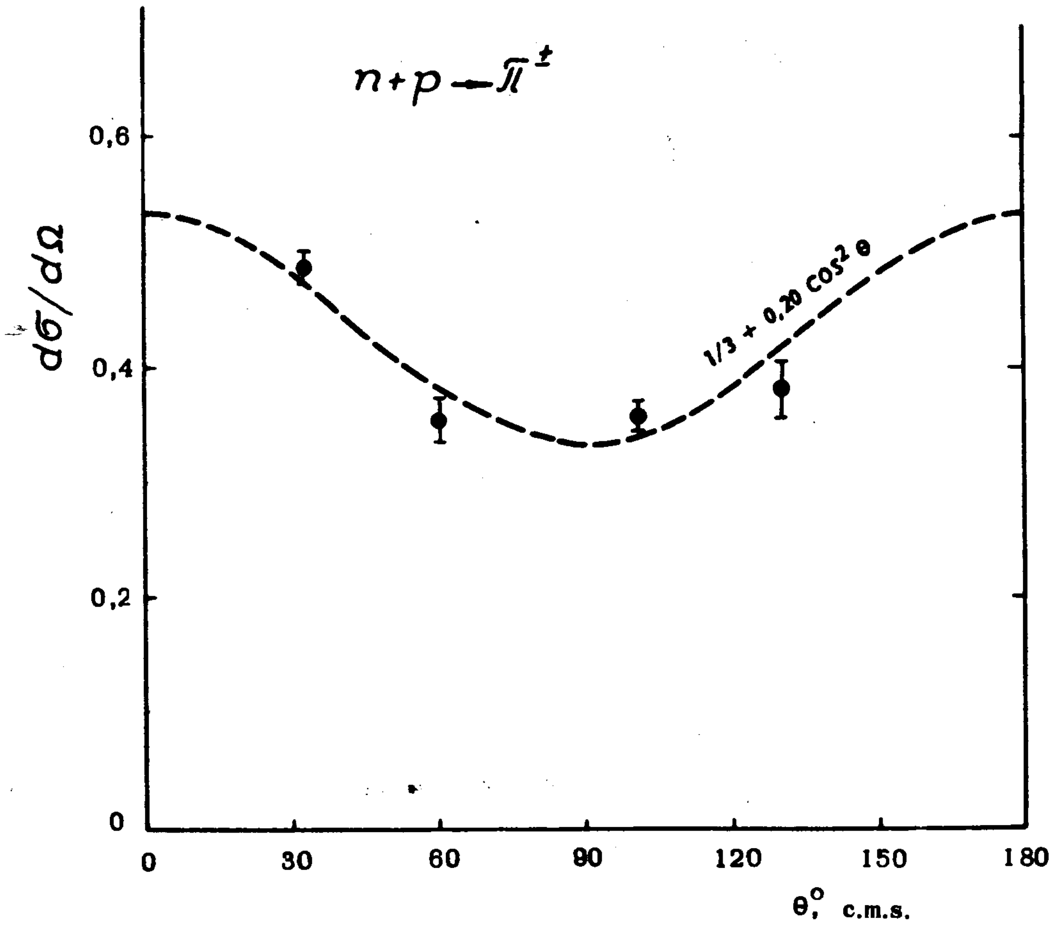


Fig. 3. Angular distribution of charged pions produced in n-p collisions at 590 MeV mean neutron energy.

$$f^{\pm}_{pn}(\theta) \sim 1/3 + (0.20 \pm 0.04)\cos^2\theta. \qquad (6)$$

The comparison of the yields of charged pions of various signs has shown that angular distributions for each of two reactions (3) are symmetric respectively to 90°. This is evidently a consequence of the smallness of the contribution value of a nonresonant transition where in the final state nucleons and pion have zero orbital momentum. In the small energy region (400 MeV) where this transition is intensive and can give essential interference considerable asymmetry of angular distribution of pions in reactions (3) was observed earlier/2/.

Obtained by integrating (6) the total cross section of reaction (3) turned out to be considerably less than in the previous papers:

$$\sigma^{+}_{pn} = \sigma^{-}_{pn} = (1.20 \pm 0.20)\ 10^{-27}\ \text{cm}^2.$$

The above results are of a preliminary character. The authors are running measurements at other angles.

At present at our laboratory we have got a lot of information on the cross sections of all the reactions of pion production in nucleon collisions at an energy of incident nucleons about 600 MeV/3–6/. The averaging of the results of various investigations provides the following values of the cross sections at an energy of 590 MeV* (here and further all the cross sections are expressed in the units 10^{-27} cm^2):

$$\begin{aligned}
\sigma^{0}_{pn} &= 4.65 \pm 0.30,\\
\sigma^{0}_{pp} &= 1.85 \pm 0.12,\\
\sigma^{+}_{pp} &= 9.00 \pm 0.40,\\
\sigma^{+}_{pn} &= 1.35 \pm 0.20.
\end{aligned}$$

Let us consider these values from the point of view of the isotopic invariance hypothesis. If isotopic spin is conserved, the sums of the cross sections of neutral and charged pion production should differ just two times. Making use of the above cross sections, we obtain that the value of the ratio

$$(\sigma^{+}_{pp} + \sigma^{+}_{pn} + \sigma^{-}_{pn})/2(\sigma^{0}_{pn} + \sigma^{0}_{pp}) = 0.90 \pm 0.07$$

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* The given values refer to an effective energy of 590 MeV and are a result of averaging cross sections in a wide energy range, the neutron-energy spectrum/1/ being taken into account.

turns out, in fact, to be equal to a unit at this energy.

Now we shall define the values of two main cross sections σ_0 and σ_1 at an energy of 590 MeV. Making use of relations (5d) and (5c) we have the values 4.5 ± 1.3 and 2.6 ± 1.2, respectively. Averaging these values (they are nearly independent) we obtain the cross section

$$\sigma_0 = 3.5 \pm 1.0 .$$

If one starts with total cross sections (relation 5a), one obtains the similar value: 3.8 ± 1.1. Another cross section, σ_1 at 590 MeV is

$$\sigma_1 = 10.8 \pm 0.5$$

so the ratio of probabilities of two main processes (with T = 0 and T = 1) turns out to be considerably less than a unit:

$$\sigma_0/\sigma_1 = 0.33 \pm 0.09.$$

At 400 MeV this ratio is equal to 0.42 ± 0.14 and there are reasons to believe that it changes little in a wide energy range/6/.

At last, take one more important characteristics of the pion production process in states with T = 0, i.e., the angular distribution of pions $f_0(\theta)$. The abovesaid data of Dzhelepov, Kiselev, Oganesyan and Flyagin are in fact the first informations on angular distribution in reaction (3) obtained within accuracy which makes it possible to determine the form of the function $f_0(\theta)$. Comparing angular distribution (6) with the obtained earlier for this effective energy the angular distribution of neutral pions/5/ $f^0_{pp}(\theta) \sim 1/3 + (0.05 \pm 0.06)\cos^2\theta$, we obtain that pions produced in the reaction with T = 0 are distributed rather anisotropically:

$$f_0(\theta) \sim 1/3 + (0.7 \pm 0.2)\cos^2\theta.$$

The accuracy of the determination of the function $f_0(\theta)$ at other energies is not obviously precise to enable one to judge about the character of $f_0(\theta)$ change with energy. Thus, $f_0(\theta) \sim 1/3 + (0.2 \pm 0.6)\cos^2\theta$ at an energy of 400 MeV/2,5/.

Now we shall leave the region of high energies and turn to one of the problems of low energy meson physics - the capture process of slow pions in hydrogen. This process leads, as is known, either to the appearence of a π° meson which immediately disintegrates into two gamma-rays:

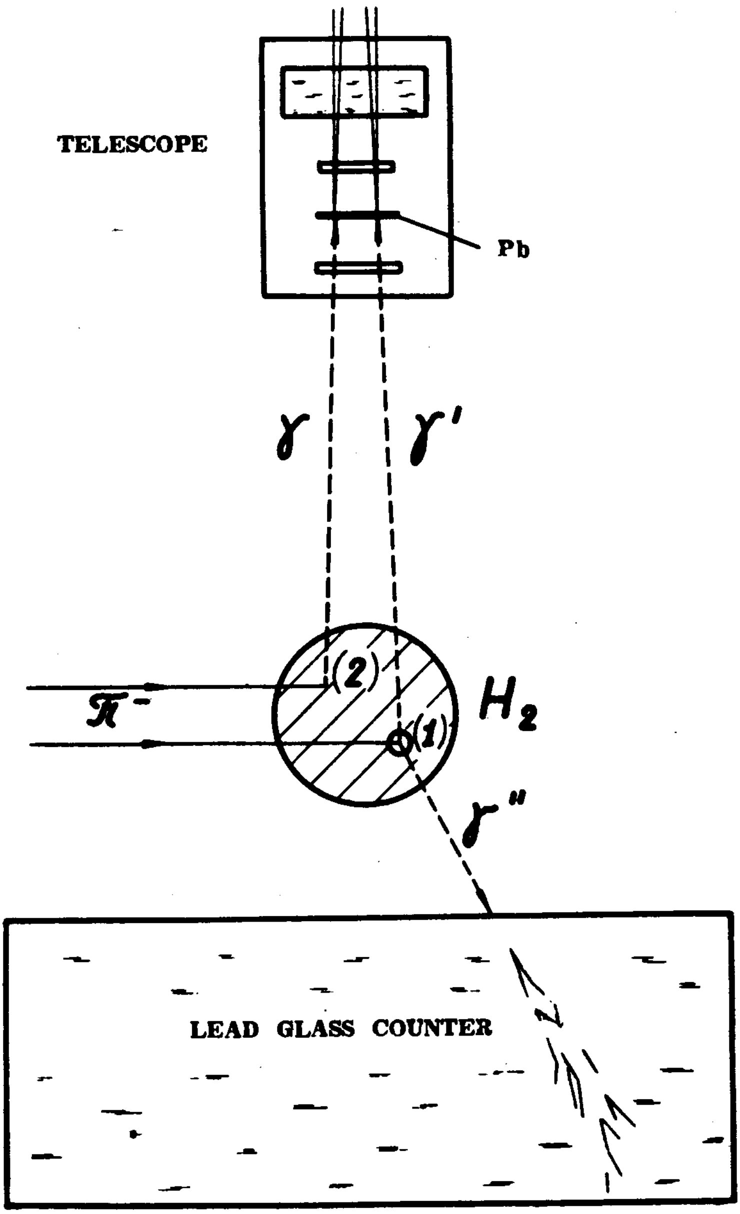
$$\pi^{-} + p \rightarrow \pi^{\circ} + n \rightarrow \gamma' + \gamma'' + n , \qquad (7)$$

or to the emission of a gamma-ray and a neutron:

$$\pi^{-} + p \rightarrow \gamma + n \qquad (8)$$

The ratio of the probabilities of reaction (7) and (8), P, was primarily measured by Panofsky/8/ after whom the value P is now usually called. This value refers directly to the problem of isotopic spin. In the frame work of modern phenomenological theory which is based on the hypothesis of isotopic spin conservation there is a profound internal connection between the processes of production and scattering of pions. The Panofsky ratio is a link between these processes since reaction (7) is the charge-exchange scattering at a very small energy and reaction (8), read backwards, is nothing but pion photoproduction. Following from this the possibility of testing the modern theory in its main point caused the hightened interest to the Panofsky ratio which took place during last years. After Panofsky who obtained that P equals approximately to a unit several attempts were undertaken in order to determine the value P in the same way. In these papers reactions (7) and (8) were identified on the basis of the gamma-ray spectra studies. However, despite the identity of methods of measurements the obtained results turned out to have a great spread which considerably exceeded the errors given by the authors. Troubles in this region redoubled by the fact that from the data on photoproduction and pion scattering the value P = 2.2 was obtained theoretically/9/, while the values obtained experimentally were grouped near 1.6.

In connection with the disagreement indicated the experiments on the determination of the Panofsky ratio value have been performed at our laboratory (A. Dunaitsev, V. Pantuev, Yu. Prokoshkin, Tang Syao-wei and M. Khachaturyan). In this work unlike in the previous ones the energy spectra of gamma-rays have not been investigated but another possibility of registering reaction (7) following from the nature of π° meson decay kinematics has been used. Analysing this kinematics one learns that gamma-rays from π° meson decay move in the lab.coordinate system so that if one fixes the direction of the emission of one of gamma-rays, one can state that the other gamma-ray moves in the opposite direction inside the cone of 46° angle. By locating the corresponding detectors set in coincidence on the way of both gamma-rays we can define the intensity of reaction (7). The plan view of such an experiment is clear from Fig. 4. The main difficulty of the last method is that due to a large value of the cone angle one of the detectors should have considerable dimensions. In order to avoid large errors of measurement this detector should have at the same time the efficiency for gamma-rays close to a unit. As such a detector



F i g. 4. Experimental arrangement for the Panofsky ratio measurement by gamma-gamma coincidences method./1/ and /2/ are reactions (1) and (2) a large lead glass Cerenkov counter with the working area 50 x 50 cm^2 has been used. A telescope with a convertor consisting of scintillation and Cerenkov counters served as the second detector. The value of the Panofsky ratio was determined directly by comparing the number of the telescope and the large counter coincidences (gamma-gamma coincidences) to the number of telescope counts which are not followed by gamma-rays hitting the large counter (if not to take the efficiency of the detectors the last number characterizes the intensity of reaction (8)).

Measurements have been carried out with the 67 MeV negative pion beam. The range curve of π^- mesons (it should be known in order to stop π^- mesons in a liquid hydrogen target) has been determined by means of a star detector/10/ sensitive only to stopped π^- mesons. Both the telescope counts and the gamma-gamma coincidence counts were entirely due to π^- mesons stopped in hydrogen which is clearly seen in Fig. 5 where the range curves measured by different methods are compared. As a characteristics of the employed technique it can be pointed out that on removing hydrogen the counting rate of the telescope decreased more than 500 times and the counting rate of gamma-gamma coincidences decreased more than 2000 times and was less than one count per 20 hours. The ratio of counting rates 'convertor in/convertor out' amounted to 10-15.

Relative efficiencies of the telescope counter and the large counter for gamma-rays of various energies have been defined experimentally with an electron beam.

As a test experiment indicating that registered gamma-gamma coincidences have a ' π^0 meson ' nature, the comparison of counting rates of gamma-gamma coincidences at various distances between the target and the large counter has been made. As is seen in Fig. 6, this counting rate does not practically change on removing the counter from the target (in the limits investigated) which is in good agreement with the calculation results and proves that all gamma-rays registered by the large counter do emerge from the target inside the narrow cone.

Several sets of measurements have been performed which have provided close values of P. Taking into account errors connected with the determination of the efficiency of the large counter (4%) and that of the telescope (2%) and the statistical accuracy of measurements (4%), the value of the Panofsky ratio is obtained with 6%:

$$P = 1.40 \pm 0.08.$$

Considering this result one should point out that at present the relation between the experiments and the theory concerning the problem of the Panofsky ratio has somewhat changed not in favour of the theory. If primarily experimental data of the Panofsky ratio were doubtful, now this value is known within the accuracy not less than 10%. At the same time it has been shown that the accuracy within which the value P can be predicted by theory is not high ($\approx$ 20%) due to great difficulties arising in

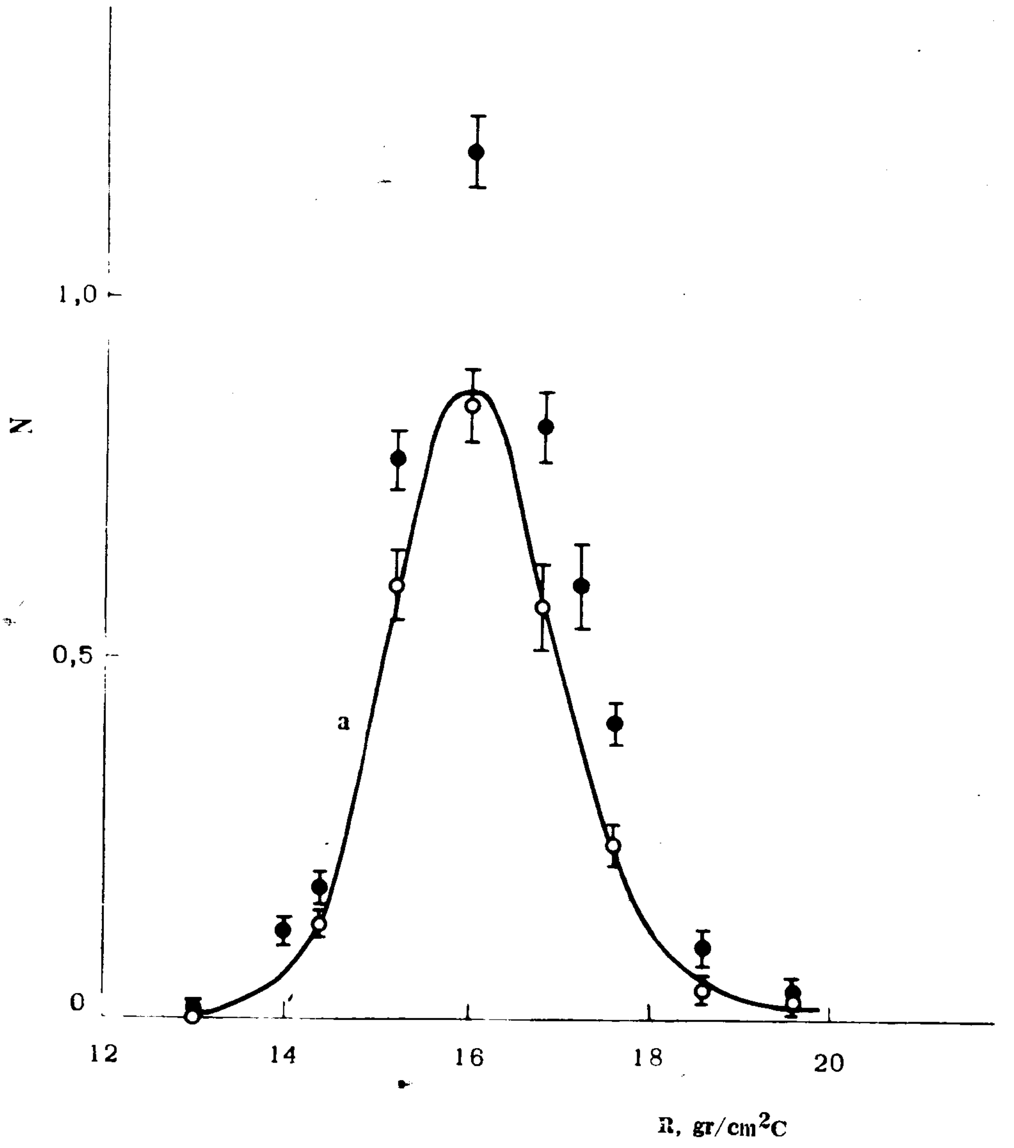
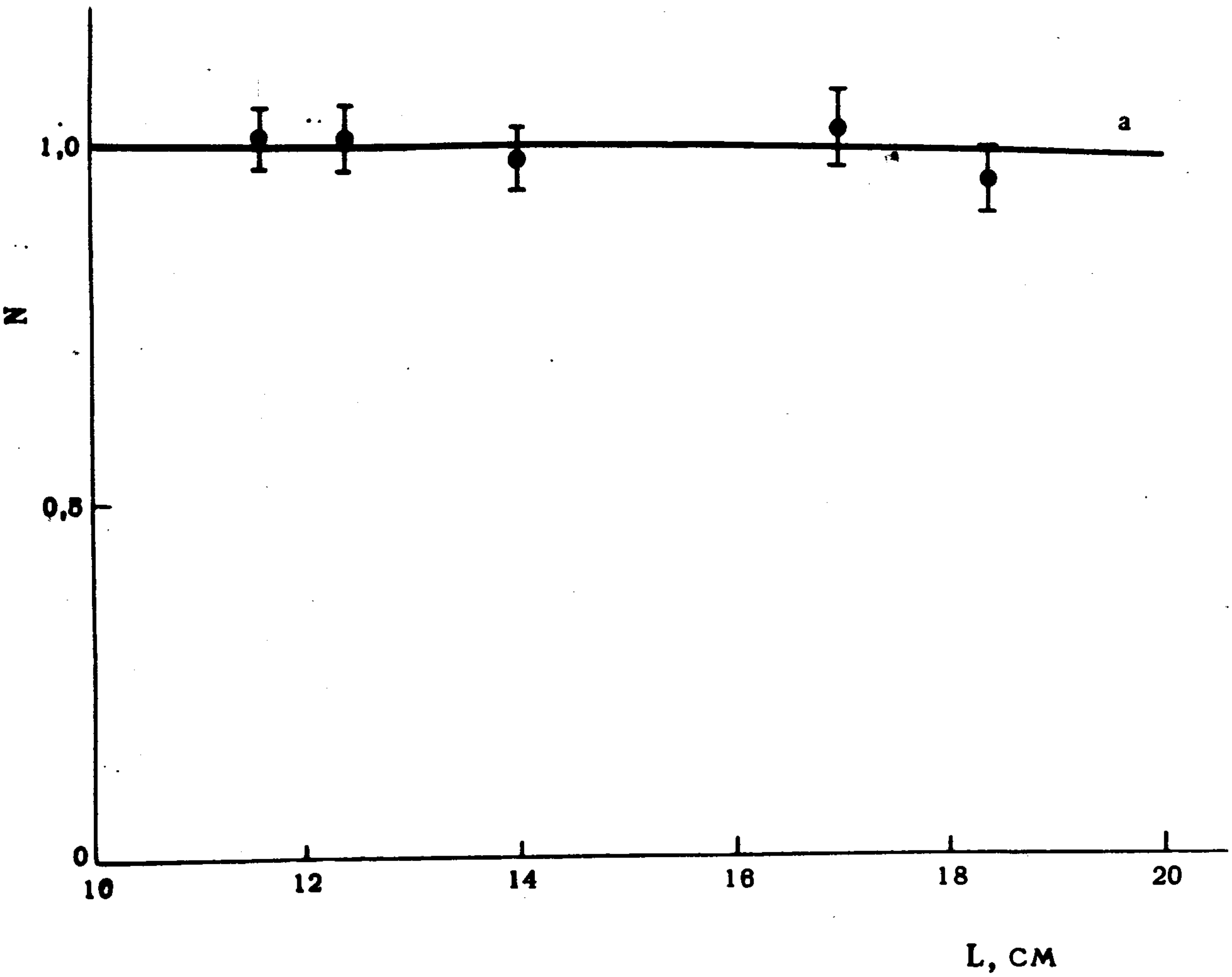


Fig. 5. **Range curves of negative pions N (R) (in relative units);**
a **is measured by means of a star detector;**
ɸ - gamma-gamma coincidences;
ɸ - telescope counting rate.



F i g. 6. Gamma-gamma coincidence counting rate N versus the distance L between the target and the large counter. *a* is a calculated curve.

the extrapolation of data on scattering and photoproduction up to zero energy[11]. On the other hand, the value of the Panofsky ratio has been obtained in the last theoretical investigations to be closer to the experimental value[11,12]. Further new advances in this branch of meson physics should be expected evidently only after the improvement of the existing theory.

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