The Possibility of the Formation of Λ^0-Particles by Protons with Energies up to 700 mev*

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An attempt was made to observe the formation of Λ^0-particles in collisions of 670 mev protons with carbon nuclei. In principle, the experiment allowed the detection of Λ^0-particles with the decay scheme $\Lambda^0 \to n + \pi^0$. Gamma-rays from the decay of π^0-mesons were detected by means of a telescope of scintillation and Cerenkov counters. It was found that the cross section for the creation of Λ^0-particles has a value of $\sigma_{\Lambda^0} \lesssim 10^{-31}$ cm^2/nucleon. Conclusions are drawn on the mechanism of creation of Λ-particles.

INTRODUCTION

THE mechanism of the creation of hyperons is unknown as yet. In earlier papers[2,3], difficulties were pointed out as to the explanation of the existence of heavy mesons and hyperons (in particular, the Λ^0-particles) which are created with a high probability in high energy collisions and have long lifetimes. An attempt to eliminate such difficulties leads to the following alternative: either the process of the formation of Λ^0-particles is not the reverse process of their decay, or, conversely, the process of their creation is the reverse of the decay process; but then the matrix element depends exceptionally strongly on the energy. This strong dependence of the matrix element on the energy could be found, for instance, in the case of a very large spin of the particles.

The first possibility was examined in references 2 and 3, where a conclusion was reached on the basis of a phenomenological analysis of the experimental data relative to the creation of Λ^0-particles and heavy mesons as to the possibility of the following transformation scheme of the nucleon:

$$(N) \rightleftarrows (\Lambda^0) + (\text{heavy meson}) \; (N \equiv \text{nucleon}) \qquad (1)$$

The above scheme describes a virtual transformation of the nucleon, analogous to the Yukawa process $(N) \rightleftarrows (N) + (\pi)$. The heavy meson requires a strong interaction between the nucleon and the Λ^0-particle. The scheme (1) permits us to put aside the difficulties connected with the duration of the lifetime and the probability of formation, not only of the Λ^0-particles, but also of the heavy mesons.

Certain indications of the correctness of the scheme (1) were obtained, for example, in the experiments of Fowler et al[4], performed with the cosmotron. In these experiments, simultaneous formation of a Λ^0-particle and a heavy neutral meson was observed upon bombarding hydrogen with π^--mesons with an energy of 1500 mev.

THE EFFECTIVE THRESHOLD FOR THE FORMATION OF Λ^0-PARTICLES

Let us first examine the reactions of formation of the Λ^0-particles in nucleon-nucleon collisions. We will assume the above-described scheme (1) as correct. If that is the case, the cross section for the $N + N \to \Lambda^0 + N$ reaction, which has a threshold of 371 mev*, should be exceedingly small. Among the processes which in this case could have a signigicant cross section, we will examine the following:

$$N + N \to N + \Lambda^0 + \text{heavy meson} \qquad (2)$$

$$N + N \to \Lambda^0 + \Lambda^0 \qquad (3)$$

[1] M. P. Balandin, B. D. Balashov, V. A. Zhukov, B. M. Pontecorvo and G. I. Selivanov, Report of the Inst. for Nuclear Problems, Acad. Sci., USSR (1954)

[2] B. M. Pontecorvo, Report of the Inst. for Nuclear Problems, Acad. Sci., USSR (1951); J. Exper. Theoret. Phys. USSR **29**, 140 (1955); Soviet Phys. **2**, 135 (1956)

[3] A. Pais, Phys. Rev. **86**, 663 (1952)

* The present paper is based on the results of work performed in 1954 and was described earlier in a report of the Institute for Nuclear Problems of the Academy of Sciences of the USSR[1].

* The mass of the Λ^0-particle is assumed to be equal to 2182 m_e.

[4] W. F. Fowler, R. P. Shutt, A. M. Thorndike and W. L. Whittemore, Phys. Rev. **93**, 861 (1954)

The effective threshold for the formation of Λ^0-particles will be understood as being the lowest value among the possible thresholds corresponding to the reactions (2) and (3). The threshold of (2) cannot be evaluated because the mass of the heavy meson, M_T, which participates in the reaction, is unknown. However, if it is assumed that $M_T = 965\ m_e$, the threshold of the reaction (2) becomes 1577 mev. The reaction (3), according to the scheme (1), should proceed via intermediate virtual transitions which represent, in the first place, the emission of a Λ^0-particle simultaneously with that of a heavy meson, and then the absorption of this meson followed by the formation of a second Λ^0-particle. The threshold for this reaction is 775 mev.

In the case of the collision of a nucleon with a complex nucleus, the effective threshold δ becomes significantly lower and can be evaluated in the momentum approximation, if the intranuclear motion of the nucleons is taken into account. Assuming a maximum "Fermi energy" of the nucleons inside of the nucleus equal to 20 mev, we obtain the value $\delta \simeq 450$ mev. It is interesting to observe that in the estimate of the threshold for the formation of the Λ^0-particles by nucleons on nuclei, no difficulties arise from the Pauli principle, such difficulties being found in the evaluation of the threshold for the formation of π-mesons by nucleons on nuclei.

Passing on to the processes of formation of Λ^0-particles by π-mesons we will consider the reaction $\pi + (N, N) \to \Lambda^0 + N$. Its threshold is equal to 40 mev. As in the previous case, with our former assumption, the cross section of this reaction should be extremely small. In connection with this, it is advisable to examine the following two reactions:

$$\pi + N \to \Lambda^0 + \text{heavy meson} \qquad (4)$$

$$\pi + (N, N) \to \Lambda^0 + \Lambda^0. \qquad (5)$$

If $M_T = 965\ m_e$, the threshold of (4) will be 757 mev. The threshold of the reaction (5) has the value of 242 mev.

A SHORT SURVEY OF THE PAPERS RELATED TO THE FORMATION OF HYPERONS BY PARTICLES WITH AN ENERGY UP TO 500 MEV

Bernardini and Segre[5] established the fact that the cross section for the formation of Λ^0-particles by bremsstrahlung photons of a maximum energy of 330 mev constitute 10^{-4} of the cross section for the creation of charged π-mesons.

The process of the formation of Λ^0-particles in collisions of protons with carbon nuclei was investigated in references 6 and 7. The cross section for this process, as found in reference 6, for a proton energy of 430 mev, has a value of less than $0.35 \times 10^{-27}\text{cm}^2$. According to more refined experiments performed by Garwin[7], the value of the cross section for the formation of Λ^0-particles in p-C collisions, even for a proton energy of 450 mev, does not exceed 10^{-31}cm^2.

A paper by Schein et al[8] is devoted to the formation of Λ^0-particles by π^--mesons on carbon, at an energy of 227 mev. In this work, 5 cases of the creation of Λ^0-particles were observed on photographic plates, but the value of the corresponding cross section is not quoted. Nevertheless, there is reason to believe that the preliminary data published by Schein contradict the results of Garwin's work. Therefore, it seemed very interesting to try to observe the formation of Λ^0-particles by nucleons of energies between 500 and 1000 mev.

EXPERIMENTAL ARRANGEMENT

The basis of the present experiment is the method proposed by Garwin. In principle, this method allows us to observe Λ^0-particles which disintegrate according to the scheme

$$\Lambda^0 \to n + \pi^0 \qquad (6)$$

The idea is that Λ^0-particles can be identified by means of the π^0-mesons being created at a certain distance from the target bombarded by protons.

Notwithstanding the fact that the decay of Λ^0-particles with the emission of π^0-mesons has not been observed, we may affirm with certainty that the probability of the process (6) must be comparable with the probability of decay according to the scheme $\Lambda^0 \to p + \pi^-$. Such an affirmation is based on the experimental fact that the process of exchange scattering of π-mesons by nucleons (the

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[5] G. Bernardini and A. Segre, Quoted in Phys. Rev. **92**, 727 (1953)

[6] A. H. Rosenfeld and S. B. Treiman, Phys. Rev. **92**, 727 (1953)

[7] R. L. Garwin, Phys. Rev. **90**, 274 (1953)

[8] M. Schein, D. Haskin, R. Glasser, F. Fainberg and K. Brown, Congres International sur le rayonnement cosmique, Bagnere de Bigorre (1953)

$\pi^- + p \to \pi^0 + n$ reaction) has a high probability.

The scheme of the experiment is indicated in Fig. 1.

The graphite target was irradiated by protons with an energy of 670 mev, which were accelerated in the synchrocyclotron of the Institute for Nuclear Problems. The displacement of the target, radially and azimuthally, was performed by remote control. The remote control provided a significant reduction of the working time for the experiment and in addition permitted measurements under steady operating conditions of the synchrocyclotron. With the aid of an electrical indicating system provided with a servo potentiometer, the position of the target was indicated with an accuracy of ±0.025 cm. The direction of motion of the circulating beam of protons was changed by reversing the magnetic field, H, of the synchrocyclotron (in Fig. 2 this is shown by the corresponding arrows). The collimator of γ-rays was directed along the radius of the equilibrium orbit of the circulating beam. It consisted of 3 blocks of lead, all being 15 cm long. All blocks had rectangular openings, 0.7 × 1.5 cm. One of these blocks was placed in the 60 × 60 × 60 cm lead shield, at a distance of 210 cm from the target. The two other blocks were placed in the iron shield, 2.7 m thick. The distance between the extreme blocks was 4 m. The γ-ray detector was placed at a distance of 8.5 m from the target. Around the detector a 15 cm thick iron shield was placed; in front, there was an additional lead shield, 60 cm thick.

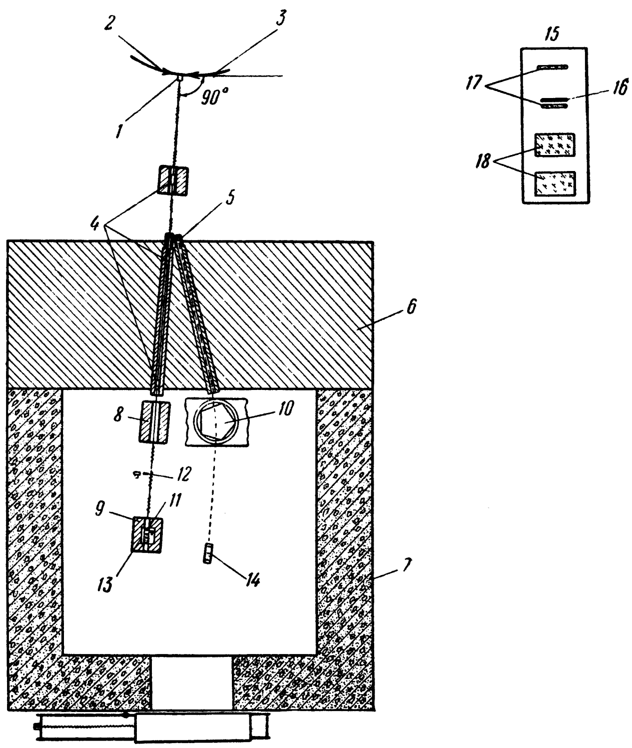

FIG. 1. Schematic diagram of the experiment. *1.* remote controlled target, 0.25 cm of C; *2.* beam of protons at reversed H; *3.* beam of protons for normal H; *4.* γ-ray collimator; *5.* π-meson collimator; *6,9.* iron shielding; *7.* concrete shielding; *8.* supplementary lead shielding; *10.* deflecting magnet; *11,16.* converter *1*; *12.* converter *2*; *13.* γ-ray detector; *14.* π-meson detector; *15.* γ-ray detector in an amplified view; *17.* toluene scintillation counter (upper, A; lower, B); *18.* Cerenkov counters, of plexiglass (upper, C; lower, D).

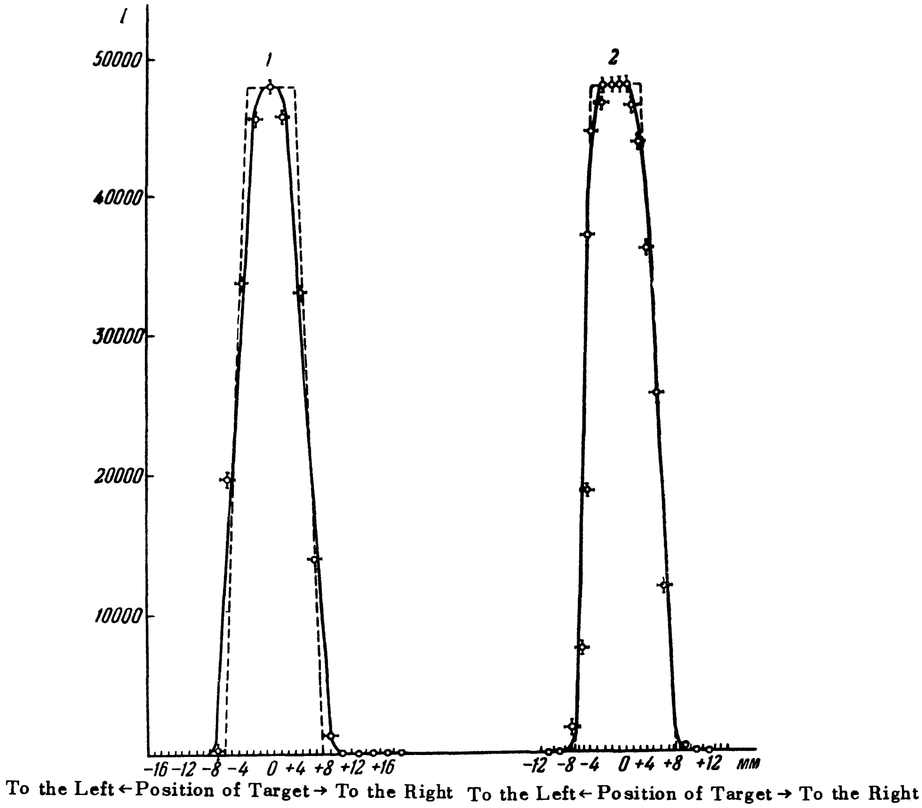

FIG. 2. Dependence of the intensity of γ-rays at the outlet of the collimator (an 0.7×1.5 cm opening) on the azimuth of the target. The full curve *1* was calculated for a target thickness of 0.5 cm; the full curve *2*, for a thickness of 0.25 cm. The dotted curves correspond to a point target.

THE γ-RAY DETECTOR

The γ-ray detector consisted of a telescope of two scintillation counters (A, B) and two Cerenkov counters (C, D). Toluene crystals were used as scintillators. The crystal of the counter A had the dimensions $5 \times 5 \times 0.5$ cm, while B was $4 \times 4 \times 0.5$ cm. In the Cerenkov counters, plexiglass of cylindrical form was used, with a diameter of 6 cm and a thickness of 3.5 cm. The light pulses from the toluene and plexiglass were registered by photomultipliers of the FEU-19 type. The pulses from each counter went through an amplifier with a pass band of 50 mc and an amplification coefficient of 100 and were fed into the input of a triple coincidence circuit. The counter A was connected for anticoincidence.

Events of the BCD-A type were registered, which corresponded to the simultaneous appearance of pulses in the three counters (B, C, D). The telescope was provided with two lead converters (*1*, *2*), both $4 \times 4 \times 0.5$ cm. The arrangement of the converters is shown in Fig. 1. The intensity of the γ-rays, I, was determined by measuring the difference in the number of events $(\text{BCD-A})_1$ given by the arrangement with the converter *1*, but without the converter *2*, and the number of events $(\text{BCD-A})_2$ with the converter *2* and without *1*. At the position of the target which coincided with the axis of the collimator, the frequency of the events $(\text{BCD-A})_2$ was 2.5-3% of the frequency of the events $(\text{BCD-A})_1$.

THE MONITOR

As a monitor, a BF_3-filled counter was used, being placed out of the limits of the lead shield indicated in Fig. 1. To clarify the possibility of using the BF_3-counter as a monitor, the following experiments were performed:

1) The indications of the BF_3-counter and those

of a supplementary telescope of three scintillation counters were registered simultaneously. With this telescope the π^--mesons passing a separate collimator and a deflecting magnet were registered (Fig. 1). On changing the intensity of the synchrocyclotron by a factor of several times, the indication of the BF_3 counter changed proportionally to the indication of the π^--meson detector.

2) The indications of the BF_3 counter were registered at various azimuthal positions of the target. The use of remote control permitted the rapid return of the target to its original position, without interruption of the operation of the synchrocyclotron. We could thus estimate the constancy of the proton beam intensity during the measurements. It was found that at a constant intensity of the circulating proton beam the indications of the counter do not depend on the displacements of the target of several centimeters.

Thus, the control experiments performed showed that the BF_3 counter can be used as a satisfactory monitor in our experiment.

MEASUREMENTS

The initial measurements constituted an investigation of the properties of the collimator. With a graphite target 0.5 cm thick, the intensity of γ-rays, I, was plotted as a function of the azimuthal target position. The obtained experimental data are represented in Fig. 2. The errors indicated in this figure are statistical. In the same graph the errors introduced by the inaccuracy in the determination of the position of the azimuth of the target are also given.

According to the experimental data obtained with a target of the originally specified thickness, with this thickness it was not possible to determine the dimensions of the region of visibility of the target. For this reason, a thinner target of graphite was used, 0.25 cm thick, during the fundamental measurements. The experiments performed with this latter target allowed the determination of the dimensions of the visible region with a much higher accuracy. Experience showed that the loss of intensity caused by the decrease of the thickness of the target was insignificant, a fact which probably can be explained by the multiple passing of the protons through the target. The curves represented in Fig. 2 by full lines were calculated for targets respectively 0.5 and 2.5 cm thick. The dotted curves correspond to a point target. One can see that the experimental data agree well with the calculated ones, this being a proof of the correct installation of the target.

The intensity of the γ-rays, I_{max}, at a position of the target which coincided with the collimator axis exceeded 10^4 times the intensity of γ-rays coming from the target at a position displaced 0.5 cm from the edge of the region of visibility. Therefore, the data on the intensity of γ-rays at a position of the target out of the limits of the region of visibility, are represented separately in Fig. 3 as functions of I_{max}. The experimental points represented in this figure for the normal and the reversed directions of the field H are normalized to the same γ-ray intensity, namely, the one at a position of the target on the axis of the collimator (0 on Figs. 2 and 3). From the Fig. 3 it is seen that for the normal as well as for the reversed direction of the field H, on approaching the target to the edges of the region of visibility, the intensity of the γ-rays increases at a rate independent of the particular side of the collimator axis on which the target is located. This supports the argument that the observed increase of the intensity of the γ-rays is not conditioned by the number of π^0-mesons from the decay of Λ^0-particles, but is connected with processes of emission of γ-rays by the walls of the collimator due to the electrons formed in the walls.

Let $\Delta(+x)$ be the difference in the intensity of γ-rays for the normal and reversed directions of the field H at a position of the target to the right of the collimator axis; analogously, $\Delta(-x)$ corresponds to the position of the target at left of the axis. Then, with the target out of the limits of the region of visibility, the intensity of the γ-rays, $I_{\Lambda^0}(|x|)$, caused by the decay of Λ^0-particles, will be expressed as

$$I_{\Lambda^0}(|x|) = \frac{\Delta(x) - \Delta(-x)}{2}.$$

Here we eliminate the error which could arise due to the difference in the backgrounds of the normal and the reversed field direction of H.

In Fig. 4 the ratio $I_{\Lambda^0}(|x|)/I_{max}$ for different distances of the target to the collimator axis is represented.

From the obtained experimental data it follows that, for a distance of the target in the 1.4-2.0 cm range, the average intensity of the γ-rays, $\overline{I}_{\Lambda^0}$, caused by the decay of Λ^0-particles, constitutes 0.1 ± 0.4 pulses/min. The comparison of this magnitude with the intensity of the γ-rays at the position of the target on the collimator axis ($I_{max} = 30{,}000$ pulses/min) indicates that the intensity

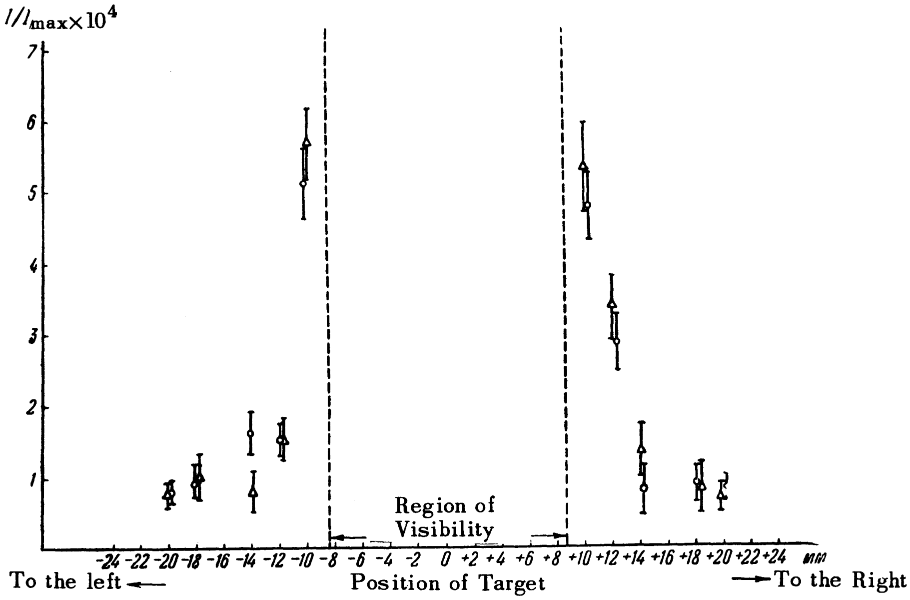

FIG. 3. The intensity of γ-rays, for a position of the target out of the limits of the region of visibility: O – for the normal, Δ – for the reversed direction of the field H.

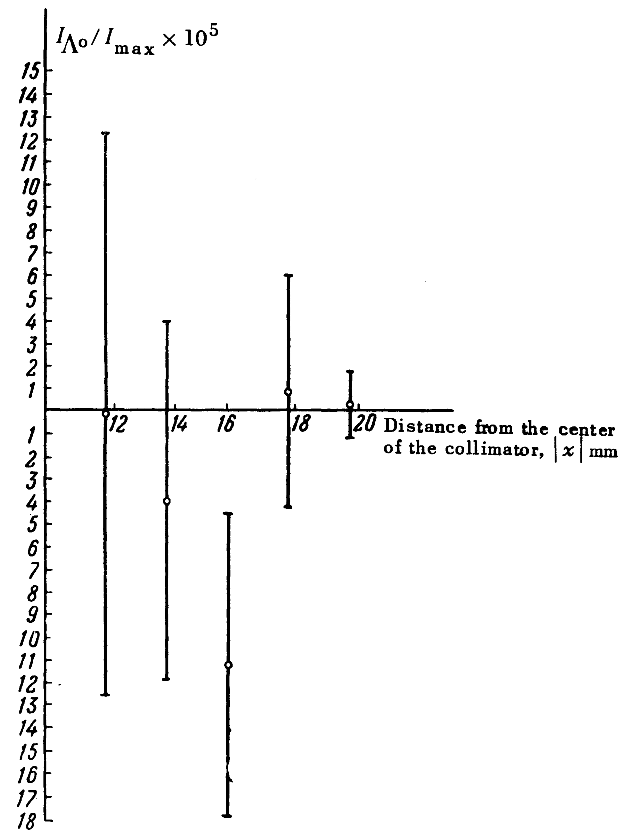

FIG. 4. Intensity of γ-rays caused by π^0-mesons from the decay of Λ^0-particles.

of rays from the decay of Λ^0-particles cannot much exceed $I_{max} \times 10^{-5}$.

The intensity I_{max} is conditioned by the decay of π^0-mesons which originate in the target. Therefore, the measurement of the creation cross section for the π^0-mesons by protons on carbon provides a possibility of determining the upper limit of the cross section $\sigma_{\Lambda^0}(C)$ for the creation of Λ^0-particles. The cross section for the creation of π^0-mesons by protons on carbon was found by us in a separate experiment[9], which was performed in an extracted beam of protons, the approximate value of the cross section being $30 \times 10^{-27}\,cm^2$. Neglecting a small correction which takes into account the difference in angular distributions of the γ-rays originated by π^0-mesons created in the target from the π^0-mesons created as a result of the Λ^0-particle decay, we shall have:

$$I_{\Lambda^0}(|x|) = I_{max}\alpha(|x|)\frac{\sigma_{\Lambda^0}(C)}{\sigma_{\pi^0}(C)}. \qquad (7)$$

Here $\alpha(|x|)$ is the fraction of Λ^0-particles which decay in the field of visibility of the collimator. Assuming the mean lifetime of Λ-particles to be 3×10^{-10} sec, which in our case corresponds to a decay mean free path of ~ 5 cm, we shall have $\alpha \approx 0.2$. Hence, by Eq. (7):

$$\sigma_{\Lambda^0}(C) \lesssim 10^{-30}\ cm^2.$$

Thus, based on the results of our experiment, one can conclude that the cross section for the creation of Λ^0-particles by protons with an energy of 670 mev cannot be greater than $10^{-31}\ cm^2$/nucleon.

DISCUSSION

The small value of the formation cross section of the Λ^0-particles in the interaction of protons with an energy of 670 mev with complex nuclei is in agreement with the hypothesis of the fundamental transformation scheme (1) of a nucleon.

Let us compare the results obtained by us with the results of Schein et al[8], where five cases of formation of Λ^0-particles by π^--mesons were observed.

The energy of the π^--meson beam in Schein's experiment was 227 mev. This value was very near to the threshold of formation of Λ^0-particles by the $\pi^- + (p, n) \to \Lambda^0 + \Lambda^0$ reaction. Having this in view, the positive results of Schein's experiment can be considered as an indication of the fact that the formation of Λ^0-particles corresponds to the virtual process $(N) \rightleftarrows (\Lambda^0) + (\pi)$. If this is true, in our work Λ^0-particles formed by the $N + N \to \Lambda^0 + N$ reaction should be observed. It must be remembered, however, that no value for the cross section for the formation of Λ^0-particles is given in the work by Schein et al, and therefore, it is too soon to affirm positively that there are contradictions between that work and ours.

It is of interest to pose a question as to what conclusion can be reached about the $N + N \to \Lambda + N$ reaction, according to the results of our experiment. It is known[4] that the cross section of formation of Λ-particles at very high energies (several thousand mev) has an order of magnitude of $10^{-27}\,cm^2$/nucleon. In the paper of Chernikov[10], the average value of the cross section for the creation of pairs of Λ-particles in collisions of nucleons with an energy of 600 mev with nuclei was estimated on the assumption that the cross section of $10^{-27}\ cm^2$/nucleon, found at high energies, corresponds mainly to the process of formation of two Λ-particles. In the same calculations, the momentum distribution of the nucleons in a nucleus was taken into account, and it was assumed that the matrix element does not depend on the energy. The cross section, estimated in this manner, appeared to be $10^{-29}\ cm^2$/nucleon, i.e., at least 100 times greater than the value for the experimental cross section obtained by us. Having in view the arbitrary nature of the assumptions made, we can conclude that there is only a slight indication of the small probability of the $N + N \to \Lambda + \Lambda$ process at high energies as compared to the probability of the processes for the creation of Λ-particles in general. A more definite conclusion could be reached if the masses of the Λ^0-particles and the positive hyperons were equal. Data from cosmic ray work also point to the conclusion that the appearance of two Λ^0-particles is a relatively improbable phenomenon. In fact, we know of no case of simultaneous observation of two events of the V^0 type, where both could be identified as Λ^0-particle decays. On the contrary, cases of simultaneous birth of Λ^0- and θ^0-particles

[9] B. D. Balashov, V. A. Zhukov, B. M. Pontecorvo and G. I. Selivanov, Report of the Inst. for Nuclear Problems, Acad. Sci., USSR (1954)

[10] N. A. Chernikov, Report of the Inst. for Nuclear Problems, Acad. Sci., USSR (1954)

were observed.

The question arises as to why the $N + N \to \Lambda + \Lambda$ reaction is improbable if the scheme (1) is true? Let us examine one of the possibilities of forbiddenness/of this reaction. The large value of the probability of formation of Λ-particles in high energy collisions conduces to the idea that in creation processes of this type the hypothesis of charge independence is applicable. However, in decay processes which have a low probability the isotopic spin cannot be conserved. Therefore, on the basis of the known decay scheme, $\Lambda \to N + \pi$, one cannot conclude a priori that the isotopic spin of the Λ-particles remains a half-integer. In connection with this, one can assume that the spin of a Λ-particle is an integer. In this case it is easily seen that the reaction $N + N \to \Lambda + \Lambda$ is forbidden. If so, the isotopic spin T_θ of the heavy meson responsible for the forces between the nucleons and the Λ-particle is very probably equal to 1/2, i.e., only the positive and the neutral modality of such mesons (θ^+, θ^0) exist.

A simple method is available for a verification of the hypothesis that $T_\theta = 1/2$. It consists in comparing the number of Λ^0-particles which are formed in hydrogen and deuterium in the bombardment of π^--mesons with an energy of the order of 1000 mev. If the above-mentioned hypothesis is correct, the cross section for the formation of Λ^0-particles in H and D must have comparable values. This follows from the fact that the neutron in a deuteron cannot contribute to the formation of Λ^0-particles, because with this assumption the reaction $\pi^- + n \to \Lambda^0 + \theta^-$ would be impossible.

CONCLUSIONS

1. The cross section for the formation of Λ^0-particles in collisions of protons with an energy of 670 mev with carbon nuclei cannot exceed 10^{-31} cm^2/nucleon.

2. In nucleon-nucleon collisions, no Λ^0-particles are created according to the $N + N \to \Lambda^0 + N$ reaction.

3. The small value of the cross section for the formation of Λ^0-particles in the interaction of protons with an energy of 670 mev with complex nuclei agrees with the hypothesis of the fundamental transformation of a nucleon according to the scheme

$$(N) \rightleftarrows (\Lambda^0) + (\text{heavy meson}).$$

4. There is some indication of the fact that at high energies the reaction $N + N \to \Lambda + \Lambda$ is improbable as compared to the processes of creation of hyperons in general. This conclusion could be reached with greater conviction if the masses of Λ^0-particles and positive hyperons were equal.

The authors deem it a pleasant duty to express their gratitude to V. V. Krivitsky and A. I. Mukhin for the help rendered in the installation of the collimator, and also to the group of co-workers of the maintenance division who permitted us to perform the present work by assuring a steady operation of the synchrocyclotron.

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191