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The Reaction $p + p \to \pi^0 + p + p$ in the Range 400-660 mev

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The energy-dependence of the differential cross section for emission of γ-rays, coming from the decays of π^0-mesons produced in the process $p + p \to \pi^0 + p + p$ is measured at 90° in the center of mass system. An analysis is made of the way in which a resonance in the $T = 3/2$, $I = 3/2$, $l = 1$ state might appear in the energy range in this reaction.

THE first measurements of the cross section of the process

$$p + p \to \pi^0 + p + p, \tag{1}$$

carried out at proton energies of 340 mev[1,2] indicated a certain forbiddenness in the reaction (1). This fact is in agreement with the assumption that the neutral meson is produced in a p-state in nucleon-nucleon collisions. The study of this reaction for protons in the energy range 450-500 mev would provide a valuable link in our knowledge of the mechanism of neutral meson production, because, as the energy available for the π^0-meson and nucleons increases, the degree of forbiddenness should decrease. The experiments carried out in the Institute of Nuclear Problems[3,4,5] and also those carried out at the University of Chicago[6] completely confirm this explanation of the forbiddenness.

In accordance with the phenomenological analysis carried out in Refs. 7,8, the experimental data of (1) are consistant with an energy dependence of the type

$$\sigma = 0{,}2\eta_{\max}^8 \cdot 10^{-27} \text{ cm}^2, \tag{2}$$

where $\eta_{\max}$ is the maximum momentum of the π^0-meson in the center of mass system, in units of $m_{\pi^0}c$. This growth of the cross section with energy corresponds to a mechanism of emission of the π^0-meson in p-states, leaving the nucleons in a state of $l = 1$.

The processes of π-meson production in nucleon-nucleon collisions,

$$N + N \to \pi + N + N' \tag{3}$$

in terms of the hypothesis of charge- independence, can be split into three groups of transitions, the total cross sections of which are denoted by σ_{10}, σ_{11} and σ_{01}. For the characteristics of these cross sections it is necessary and sufficient to study only three processes, for example, $p + p \to \pi^+ + n + p$ $(\sigma_{10} + \sigma_{11})$; $p + p \to \pi^0 + p + p$ (σ_{11}) and $n + p \to \pi^+ + n + n$ $[1/2(\sigma_{11} + \sigma_{01})]$. The process $p + p \to \pi^0 + p + p$ occupies a special position, since it corresponds to only one group of transitions, while all of the remaining processes include two groups of transitions.

For the considerations of (3) it is convenient to separate off the sub-system of two nucleons, characterizing it by the relative motion of the nucleons and by the motion of the sub-system as a whole. In the energy-region near to threshold, the angular momentum of the two-nucleon sub-system has an upper limit of one or two. It is useful to take into account the interaction between nucleons phenomenologically.

Besides the interaction between nucleons, it is necessary also to note the interaction of the π-meson with the nucleon, which appears to have a resonance character in the state with $T = 3/2$, $I = 3/2$ and $l = 1$. This is indicated by three groups of experiments: the process of scattering of π-mesons on protons, the process of photoproduction of π-mesons, and also the process of production of π^+-mesons in p–p collisions with formation of deuterons, $p + p \to \pi^+ + d$. In the first two cases the interaction in the state with $T=3/2$, $I=3/2$ $l = 1$ appears directly; in the case of the reaction $p + p \to \pi^+ + d$ the resonance leads to an in-

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[5] L. M. Soroko, Reports (Otchet) Inst. Nucl. Prob., Acad. Sci. (U.S.S.R.), 1952.

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[8] M. Gell-Mann and K. M. Watson, Annual Review of Nuclear Science 4, 245 (1954).

crease in the cross section by a factor[7] 3-5, and the non-monotonic character of the energy dependence of the transition matrix element of this reaction, established in Ref. 9, appears clearly.

An analogous appearance of the resonance interaction in the state with $T = 3/2$, $I = 3/2$, $l = 1$ can be expected in all remaining processes of meson production, in particular in the processes $p + p \to \pi^+ + n + p$ and $p + p \to \pi^0 + p + p$. However, there is an essential difference between these last processes and the reaction $p + p \to \pi^+ + d$.

In the first place, one must take into account the fact that the process (3) is connected with a considerably larger number of transitions than the reaction $p + p \to \pi^+ + d$. In order to trace which of the possible transitions can be connected with a resonance in the state $T = 3/2$, $I = 3/2$, $l = 1$ we divide the system of three particles $\pi + N + N$ into two sub-systems: $(\pi + N)$ and (N). The total angular momentum of the sub-system $(\pi + N)$ in the case of resonance should be $I = 3/2$ (and the orbital momentum $l = 1$, i.e., the sub-system is in a $^2P_{3/2}$ state). To this sub-system we add the second nucleon, having various orbital momenta relative to the sub-system. As a result we obtain the possible states of the three particles shown in Table 1.

TABLE 1

Total angular momentum I	0		1		2		3		4
Total parity	+	−	+	−	+	−	+	−	+
Possible states	$^2P_{3/2}d_0$	$^2P_{3/2}p_0$	$^2P_{3/2}s_1$	$^2P_{3/2}p_1$	$^2P_{3/2}s_2$	$^2P_{3/2}p_2$	$^2P_{3/2}d_3$	$^2P_{3/2}p_3$	$^2P_{3/2}d_4$
			$^2P_{3/2}d_1$	$^2P_{3/2}f_1$	$^2P_{3/2}d_2$	$^2P_{3/2}f_2$	$^2P_{3/2}g_3$	$^2P_{3/2}f_3$	$^2P_{3/2}g_4$

It would seem that the sharpest appearance of the resonance in the state with $T = 3/2$, $I = 3/2$, $l = 1$ can be expected in those cases where the second nucleon is in an s-state relative to the $(\pi + N)$ sub-system. If this is so, then the states $^2P_{3/2}s_1$ and $^2P_{3/2}s_2$ turn out to be most essential. To the first of these, $^2P_{3/2}s_1$, corresponds an initial nucleon with even l and total angular momentum $I = 1$, which can occur only in case $T_{\text{initial}} = 0$. This means that the $^2P_{3/2}s_1$ state is not connected with the resonance since $T_{\pi N} = 3/2$ and $T_N = 1/2$ cannot be combined to give $T = 0$.

Therefore, we will consider only the $^2P_{3/2}s_2$ state, to which only one of the initial nucleon states can lead, namely $^1D_2$. In terms of the first type of classification of states, the transitions arising in this case are

$$^1D_2 \to {}^3S_1p_2, \quad ^1D_2 \to {}^3P_2s_2, \quad ^1D_2 \to {}^3P_{1,0}d_2.$$

The first of these is essential only in the reaction $p + p \to \pi^+ + n + p$, wheras the remaining two relate to the process $p + p \to \pi^+ + n + p$, and to the process $p + p \to \pi^0 + p + p$. The latter transitions should, it would appear, occur with less probability than the first, since the nucleons are in p-states. Besides the smaller cross section in these transitions, the emission of a proton in a p-state leads to a distortion of the energy dependence of the cross-section, for example, to a displacement of the maximum to higher energies.

Thus the resonance character of interaction in the $T = 3/2$, $I = 3/2$, $l = 1$ state, which occurs in the 'purest' aspect only in case of the transition $^1D_2 \to {}^3S_1p_2$ in the reaction $p + p \to \pi^+ + n + p$, can be covered up by other non-resonance transitions. In case of the reaction $p + p \to \pi^0 + p + p$ there is no basis to expect a sharp appearance of the resonance which could lead to a non-monotonic dependence of the cross section $p + p \to \pi^0 + p + p$ in the region of π-meson energies ~ 160 mev.

In the second place, the reactions $p + p \to \pi^+ + d$ and $N + N \to \pi + N + N'$ differ because of the statistical factor. Namely, the statistical factor of the cross section of the reaction $N + N \to \pi + N + N'$ depends, in the non-relativistic region, on the maximum meson momentum as η^4_{max}, whereas for the reaction $p + p \to \pi^+ + d$ the statistical factor is proportional to the

[9] M. G. Meshcheriakov and B. S. Neganov, Dokl. Akad. Nauk. SSSR 100, 677 (1955).

first power of the momentum.

In the third place, the reaction $N + N \to \pi + N + N'$ gives rise to a wide spectrum of π-mesons, so that an integral effect enters into the total cross section, leading to a smoothing out of the resonance effect even in those transitions where it occurs.

In this work the energy-dependence of the cross section, reaction (1), was studied at proton energies of 400 to 660 mev. Measurements were carried out at an angle of $\sim 90°$ of the differential cross section for γ-rays from the decay of π^0-mesons produced in the process $p + p \to \pi^0 + p + p$. If it is assumed that there is not a sudden variation in the π^0-meson emission with respect to angle or energy, then the observed cross section reflects the energy dependence of the total cross-section $\sigma^{\pi^0}_{pp}$.

1. EXPERIMENTAL ARRANGEMENT

The experiment was carried out with the 657 mev proton beam of the synchro-cyclotron of the Institute of Nuclear Problems of the Academy of Science of the U.S.S.R. The experimental arrangement is shown in Fig. 1. The proton beam emerged from a concrete shielding wall through a 4 m collimator, traversed the ionization chamber and hit the target which was liquid hydrogen contained in a glass Dewar. The ionization chamber served as a monitor, and also as instrument for measuring the intensity of the proton beam. Calibration of this chamber was carried out in a separate experiment[10]. The working part of the target was defined within the volume of liquid hydrogen by lead collimators, which shielded the γ-ray counter from radiation arising from interactions of the protons in the glass walls of the Dewar. The mean path of protons in this working part of the target, taking into account the penumbra formed by the collimators, was about 8 cm. The measurement of the background was carried out with the glass Dewar full of hydrogen gas at atmospheric pressure.

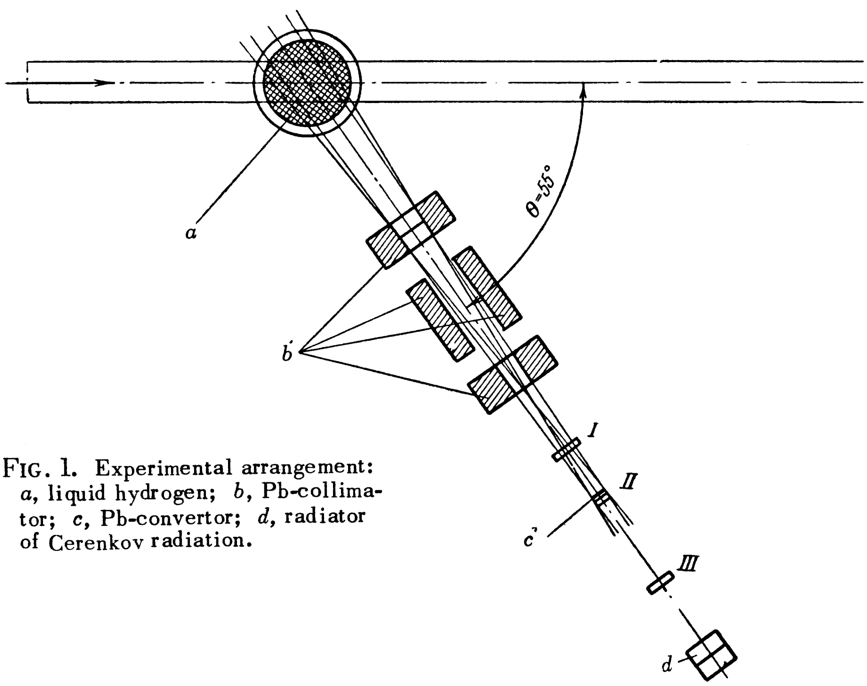

FIG. 1. Experimental arrangement: a, liquid hydrogen; b, Pb-collimator; c, Pb-convertor; d, radiator of Cerenkov radiation.

Proton beams of energy less than 657 mev were obtained by inserting blocks of polythene in the path of the beam in the collimator to slow them down. At energies of 400-500 mev the energy spread of the beam of protons was ±12 mev.

The passage of the protons through the retarding blocks was accompanied by various processes in the blocks which made the experimental conditions worse. Thus, for example, the slow charged particles emerging from the blocks created misleading ionization in the ionization chamber. The necessity

[10]B. S. Neganov, O. V. Savchenok and L. M. Soroko, Reports (Otchet) Inst. Nucl. Prob., Acad. Sci. (U.S.S.R.) 1954.

which was found experimentally, of introducing corrections on account of this effect arose in all experiments with proton beams of diminished energy. In the study of process (1), there occurred the additional hindrance of charge-exchange neutrons produced in the retarding blocks from the exchange interaction of protons in collisions with carbon atoms. Such neutrons impinging on the liquid hydrogen target initiate the process $n + p \rightarrow \pi^0 + n + p$, the relative yield of which exceeds the yield of process (1), especially in the region of reduced proton energy. In the worst conditions this background did not exceed 15%.

In this experiment γ-rays from π^0-meson decays were registered by a system consisting of a telescope and a Cerenkov counter. In the experiments determining the absolute cross-section only the telescope was employed. The telescope consisted of three scintillation counters (tolane). Counters II and III were in coincidence and counter I in anti-coincidence with II and III. A lead converter of dimensions 2×2 cm^2 and thickness 0.5 cm was inserted or left out before counter II.

The Cerenkov counter had two photo-multipliers arranged vertically, between which was placed a plexiglass radiator in the form of a cube cut into two sections. Each section of the cube was joined optically with only one of the photo-multipliers. Pulses from each photo-multiplier were fed into amplifying channels. After shaping the amplitudes and lengths of the pulses, they acted in a system of two-fold coincidence, so that the major part of the noise in each photo-multiplier was suppressed. An analogous arrangement was also used in the telescope described above.

Measurements of the intensity of Cerenkov radiation[11] for fast electrons in the plexiglass showed that the number of photo-electrons was about 8 for a 2.5 cm thickness of plexiglass. For such a small number of photo-electrons it was necessary for the system to be triggered by the emission of a single electron. For this, with an amplification coefficient of the photo-multiplier of 5×10^5 and an output capacity of the photo-multiplier ~ 5 pF it was necessary to have a further amplification of approximately 200. The stages of the wide-band amplifier employed had a complicated correction, the parameters of which were found using the nomogram and table given in Ref. 12.

2. EFFICIENCY OF COUNTING CHARGED PARTICLES OF VARIOUS VELOCITIES BY CERENKOV RADIATION

The experiment to define the efficiency of counting charged particles by Cerenkov radiation was carried out in the following fashion. Two telescopes I and II in coincidence were placed at angles relative to the proton beam so as to register p–p elastic scattering events. The targets in this experiment were of paraffin and carbon. Immediately behind the telescope registering high energy protons a Cerenkov counter was placed so as to be traversed by all protons which were registered in the telescope in front. Pulses from the counter and telescopes acted in coincidence. In this experiment the number of coincidences between telescopes was compared with the number of times there was also a coincidence with the Cerenkov counter. The following values were obtained for the dependence of the efficiency of counting the Cerenkov radiation on the energy of the proton counted by the telescope:

330 mev	380 mev	440 mev	600 mev
(3 ± 4) %	(22 ± 5) %	(37 ± 3) %	(55 ± 7) %

In addition to this experiment a measurement in the direct beam of 450 mev protons of decreased intensity was carried out. In this the efficiency found was (36 ± 4)%. The results of these measurements show that the Cerenkov counter is to the extent given really a threshold counter.

Together with this even at high proton velocities a counting efficiency less than 100% was observed. It is possible to explain the incomplete efficiency in the region of the plateau in counter characteristics if considerable fluctuations in the number of photo-electrons are assumed. As a consequence of this, the process in which no electron is emitted in the photo-cascade or in which the electron disappears before it starts a shower, has a high probability. The efficiency of the Ceren-

[11] J. Marshall, Phys. Rev. **86**, 685 (1952).

[12] G. V. Braude, K. V. Epaneshnikov and B. Ia. Klumushev, Radiotekhnika **4**, 24 (1949); **5**, 16 (1950).

kov counter can increase, it would appear, if the sensitivity of the photo-cascade is made greater and if the loss of electrons at the initial stages of development of the shower is decreased.

3. DEPENDENCE OF THE CROSS SECTION $(d\sigma/dw)^{\gamma}_{90^\circ}$ ON THE ENERGY OF THE INCIDENT PROTON

In the relative measurements of the cross section $(d\sigma/d\omega)^{\gamma}_{90^\circ}$, the system of telescope and Cerenkov counter was employed. The efficiency of this system of counting γ-rays at different proton energies was calculated in the following way. The following were taken in succession into the calculation: The 'vanishing' of the electron and positron in traversing the lead converter on account of bremsstrahlung, multiple scattering of electrons in the lead converter, and also the experimental value for the cross section of pair production in lead. The character of the γ-spectra arising at different proton energies was calculated under the assumption that the energy spectrum of the π^0-mesons was determined by only the statistical factors, and that the π^0-mesons were distributed isotropically in the center of mass of the two protons.

In addition, a rough evaluation of the absolute cross section was carried out in experiments where only the telescope was employed. In this case $(d\sigma/d\omega)^{\gamma}_{90^\circ} = (4{,}5\pm1{,}8)\times10^{-28}$ cm^2/sterad, and the total cross section $\sigma^{\pi^0}_{pp} = (2{,}8\pm1)\times10^{-27}$ cm^2, if the π^0-mesons are distributed isotropically in the center of mass system.

4. DISCUSSION OF RESULTS

The results obtained in this work are given in Fig. 2. The most detailed measurements were

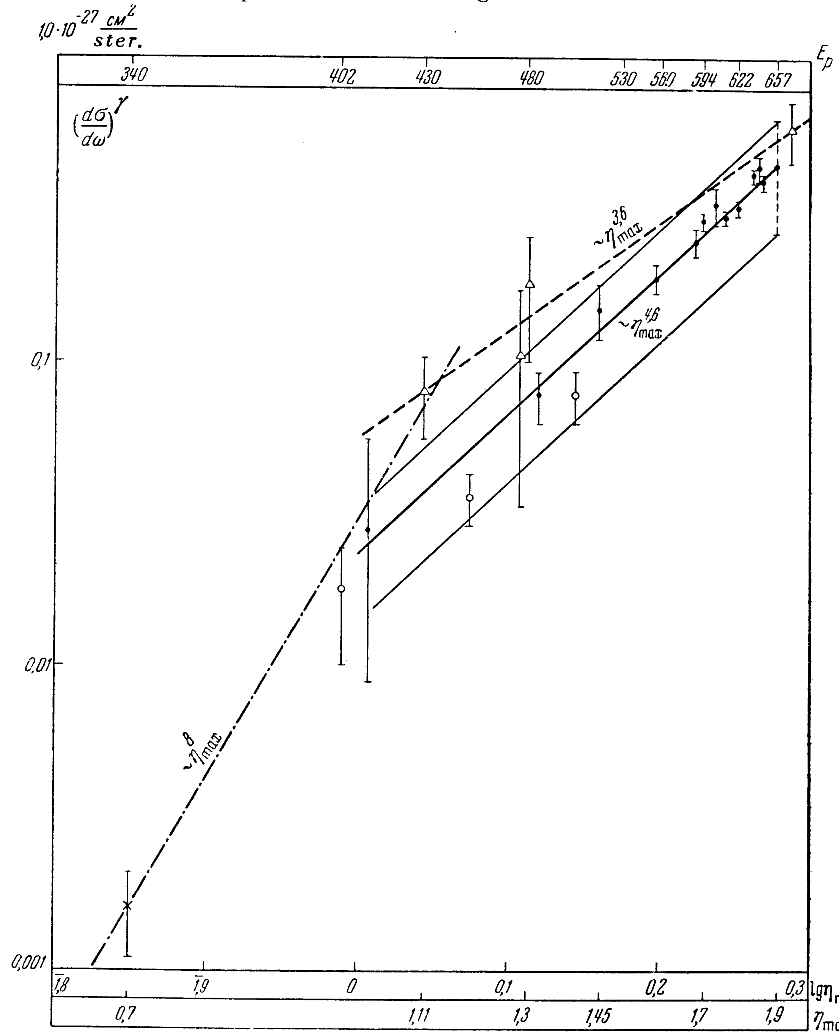

FIG. 2. ● and ○ — $(d\sigma/d\omega)^{\gamma}_{\sim90^\circ}$, in this experiment, × — $(d\sigma/d\omega)^{\gamma}$ according to Ref. 2, Δ — $(d\sigma/d\omega)^{\gamma}_{0^\circ}$ according to Ref. 4-6, 13.

carried out at the maximum energy of the π^0-mesons in the region 120-150 mev (proton energy of 580-660 mev), at which energies non-monotonic variations with energy of the total cross sections are observed in the reaction $p + p \to \pi^+ + d$ and in the processes of scattering and photo production of mesons in hydrogen. In the present experiment a non-monotonic change of the cross section $(d\sigma/d\omega)^{\gamma}_{90^\circ}$ in the range of proton energies 580-660 mev was not observed. If we assume that in the given region no sharp change occurs in the dependance on energy or angle of the cross section for emission of a π^0-meson, then this conclusion relates also to the total cross-section $\sigma^{\pi^0}_{pp}$. This result is in accordance with the conclusions arrived at at the beginning of this article. Results of others are also shown on Fig. 2. A list of these is given in Table 2.

TABLE 2

Proton energy in mev	Maximum momentum of the π^0-meson in c.m. system	$(d\sigma/d\omega)^{\gamma}_{0^\circ}$ in the lab system in units of 10^{-28} cm^2 / sterad	$(d\sigma/d\omega)^{\gamma}_{0^\circ}$ in c. m. system (10^{-28} cm^2/sterad)	total cross-section σ^{π^0} (10^{-28}/cm^2)	assumed angular distribution of the π^0-meson.	References
340	0,70	—	$(1,6\pm0,5)\cdot10^{-2}$	$(1,0\pm0,3)\cdot10^{-1}$	—	[2]
430	1,11	2	0,8	$4,5\pm1,5$	$a+\cos^2\theta$	[6]
460	1,23	—	—	4 ± 2	$\cos^2\theta$	[3]
—	—	—	—	$5\pm2,5$	isotropic	—
480	1,30	$2,6\pm1,7$	$1,04\pm0,7$	$4,4\pm3$	$\cos^2\theta$	[4]
480	1,30	$4,5\pm2$	$1,8\pm0,8$	$(1,05\pm0,45)\cdot10$	isotropic	[5]
—	—	—	—	$(0,62\pm0,28)\cdot10$	$\cos^2\theta$	—
650	1,88	—	—	$(3,6\pm0,7)\cdot10$	$\cos^2\theta$	[15]
—	—	—	—	$(3,0\pm0,6)\cdot10$	isotropic	—
670	1,94	—	$5,9\pm1,3$	$(3,7\pm0,8)\cdot10$	isotropic	[13]

The solid line shows the dependence according to the power law

$$(d\sigma/d\omega)^{\gamma}_{90^\circ} = C_1\eta_{\max}^{4,6\pm0,5}$$

which approximates to the experimental results obtained in this experiment for $1 < \eta_{\max} < 1.9$. The magnitude of the absolute error for $E_p = 657$ mev is shown on Fig. 2 by dashes. Other results[4-6,13] for $\theta = 0^\circ$ are represented by the dashed line which corresponds to the power law

$$(d\sigma/d\omega)^{\gamma}_{0^\circ} = C_2\eta_{\max}^{3,6}$$

for $1 < \eta_{\max} < 1.9$.

All of these results can be reconciled with a dependence of the total cross section for production of π^0-mesons in process (1) in the region $1 < \eta_{\max} < 1.9$ according to the power law

$$\sigma^{\pi^0}_{pp} \sim \eta^{\alpha}_{\max}, \quad \text{where } \alpha \approx 4.$$

It is of interest to compare these results with the energy dependence of the total cross section $\sigma^{\pi^0}_{pp}$ which would be expected if the transition matrix element is constant. Calculation[16] leads to the expression

$$\times \quad \sigma^{\pi^0}_{pp} = \text{const}\,\frac{1}{v} \int_0^{p_{\max}} [M(W - \sqrt{p^2+m^2}) - {}^1/_4\, p^2]^{1/2} p^2 dp, \tag{5}$$

[13] A. A. Tiapkin, M. S. Kozodaev and Iu. D. Prokoshkin, Dokl. Akad. Nauk SSSR **100**, 689 (1955).

[14] W. E. Crandall and B. J. Moyer, Phys. Rev. **92**, 749 (1953).

[15] B. D. Balashov, V. A. Zhukov, B. M. Pontecorvo and G. I. Selivanov, Report (Otchet) Inst. Nucl. Prob., Acad. Sci. (U.S.S.R.), 1954.

[16] E. Fermi, *Elementary Particles*, Yale University Press, 1951.

where v is the velocity of the incident proton, p is the momentum of the π-meson, M and m are the masses of nucleon and π-meson respectively, W is the kinetic energy of two nucleons in the center of mass system. To derive this formula the relation between energy and momentum for the π-meson was taken as $\mathcal{E}_\pi=\sqrt{p^2+m^2}$, and for the nucleon as $\mathcal{E}_N-M=p_n^2/2M$. The choice of the last relation is justified by the fact that the maximum nucleon energy in the region considered does not exceed 75 mev.

In the energy region studied in this experiment the dependence shown in (5) can be approximated by a power law of the form: $\sigma_{pp}^{\pi^0}=\text{const}\ \eta_{max}^{3.6}$. As is known, in the region $\eta\ll 1$, the statistical factor is proportional to η_{max}^4.

Through comparison of this calculated dependence (power equal to 3.6) with the given experiments (power of approximately 4) it can be concluded that the energy dependence of the transition matrix element for (1) is small.

In conclusion the author expresses his gratitude to M. G. Meshcheriakov, L. I. Lapidus and S. M. Bilen'kii for discussion of experimental results, and also to A. S. Kuznetsov who took part in the construction of the electronic apparatus.

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The Possibility of a Two-Step Excitation Mechanism in Sulfide Phosphors

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Experimental data on the kinetics of luminescence in strongly quenched phosphors indicate that in spite of widely held ideas to the contrary, the bimolecular theory is not applicable. An interpretation of the experiments in terms of a two-step phosphorescence excitation mechanism is presented. It is shown that a two-step excitation process is responsible for photoconductivity in CdS (Cu) having high copper concentrations. Moreover luminescence in this material exhibits properties typical of strong quenching.

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1. The kinetics of "fast" luminescence in sulfide phosphors (for example, ZnS, CdS, etc.) has been studied in a number of investigations[1] in which the tau-meter method[2] was employed. At temperatures far below the temperature at which quenching occurs, the growth and decay curves are approximated by functions which do not satisfy any simple kinetic equations. The possibility of interpreting these relaxation curves or of drawing even qualitative conclusions concerning processes in these phosphors is very remote. The expression which approximates the decay curve

$$I\sim(1+at)^{-\alpha}. \tag{1}$$

(where, for ZnS-Cu at room temperature, α has a value of the order of 0.7) cannot be correct *a priori* if the time is allowed to increase without limit because of the infinity which appears in the stored light-sum. Moreover, Eq. (1) is not valid at the very beginning of the decay curve (for example in the region of 100-90 per cent of the steady-state luminescence); using a method developed by the author[3] in which the relaxation curves are electrically differentiated, it has been shown that the curve in (1) is affected by the intensity of excitation E in a manner which is given by the expres-

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[1] V. A. Arkhangel'skaia, A. M. Bonch-Bruevich, N. A. Tolstoi and P. P. Feofilov, Dokl. Akad. Nauk SSSR 64, 187, (1949); J. Exptl. Theoret. Phys. U.S.S.R. 21, 290 (1951). D. B. Gurevich, N. A. Tolstoi and P. P. Feofilov, Dokl. Akad. Nauk SSSR 71, 29 (1950). V. A. Arkhangel'skaia, A. M. Bonch-Bruevich and N. A. Tolstoi, Izv. Akad. Nauk SSSR Ser. Fiz. 15, 695 (1951).

[2] N. A. Tolstoi and P. P. Feofilov, Usp. Fiz. Nauk 41, 44, (1950).

[3] N. A. Tolstoi, Izv. Akad. Nauk SSSR Ser. Fiz. 15, 712 (1951).