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PHOTOPRODUCTION OF SLOW π^0 MESONS ON COMPLEX NUCLEI

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Results of measurements of the dependence of the cross section for photoproduction of slow π^0 mesons on the mass number of the target nuclei are presented for nuclei between C and Pb. $\sigma \sim A^{2/3}$ for synchrotron γ-ray beams of maximum energy of 265 and 210 Mev. The dependence of the slow π^0 meson yield on the maximum energy of the γ-ray beam has been measured for carbon and lead. The results agree with the theory of π-meson production on the surface of the nucleus.

1. INTRODUCTION

THE photoproduction of π mesons on nuclei has been studied in a series of papers.[1-5] It was found that in all cases of complex nuclei (heavier than Al) the relationship $\sigma_A \sim A^{2/3}$ holds where σ_A is the cross section for the production by a photon of a meson on a nucleus of mass number A.

There exist two different explanations of the observed dependence of the cross section for the photoproduction of π-mesons on the mass number. The first theory[6] is based on the optical model which takes into account the finite mean free path for the reabsorption of mesons in nuclear matter. According to this theory the cross section for the photoproduction of π mesons on a nucleus of mass number A is given by

$$\sigma_A = \sigma_0 A \eta f_a, \tag{1}$$

where σ_0 is the cross section for the production of mesons on a free nucleon, and η is a factor that takes into account the nuclear binding of the nucleons inside the nucleus. The magnitude of this factor is in the general case less than unity, since the law of conservation of energy and the Pauli exclusion principle impose a restriction on the possible number of final states. However, the value of η must be approximately the same for different nuclei. f_a is the reabsorption coefficient given by

$$f_a = \frac{1}{V}\int e^{-x/\lambda_a}\,d\tau = \frac{3}{4}\frac{\lambda_a}{R}\left[1 - \frac{\lambda_a^2}{2R^2} + \frac{\lambda_a^2}{2R^2}\left(\frac{2R}{\lambda_a}+1\right)e^{-2R/\lambda_a}\right], \tag{2}$$

where λ_a is the mean free path for absorption, $R_0 = r_0 A^{1/3}$ is the nuclear radius, V is the nuclear volume, and x is the path length traversed by the meson inside the nucleus. From this it may be seen that when $2R/\lambda_a \gg 1$,

$$\sigma_A \approx \sigma_0 \eta\,[3\lambda_a / 4r_0]\,A^{2/3}, \tag{3}$$

i.e., the relationship $\sigma_A \sim A^{2/3}$ is obtained in the case when the mean free path of the meson is considerably smaller than the nuclear dimensions.

The quantity λ_a is found directly from results of experiments on the interaction of π mesons with nuclei.[7] However, in a number of cases the meson mean free path turned out to be too large to explain the dependence $\sigma_A \sim A^{2/3}$ observed in experiments on photoproduction. Therefore a second theory has arisen[8] to explain this dependence, which assumes that the formation of real mesons is possible only on the nuclear surface. Inside a nucleus the absorption of photons is accompanied by photodisintegration which has a greater probability than photoproduction of mesons. According to this theory (the theory of surface production of mesons), the relationship $\sigma_A \sim A^{2/3}$ is obtained automatically in all cases (since the nuclear surface is proportional to $A^{2/3}$). The physical picture of the phenomena occurring when high-energy photons are absorbed inside complex nuclei is given by Wilson.[9] He assumes that the absorption of a photon in the nucleus is accompanied by the production of a virtual meson on one of the nucleons, with a subsequent absorption of it by the system comprising the nucleon that gave rise to the meson and one of its neighbors. Thus the absorption of photons in nuclei leads to the photodisintegration of "quasi-deuterons,"[10] with the latter process having a greater probability than the formation of a real meson.

It has been established experimentally, by recording n-p coincidences, that such a process does in fact occur,[11] and, apparently, is the main source of photoprotons of high energy. A decision between these two theories can be made by measuring the dependence on the mass number of the cross section for the production of mesons on nuclei, for mesons of different energies. As is well known,[7] the mean free path λ_a for a meson in nuclear matter depends strongly on the meson energy, increasing as the energy decreases. Therefore as the energy of the recorded π mesons is reduced, the dependence of σ_A on A must approach a linear one (instead of $A^{2/3}$) if the first theory is valid. However, if the theory of surface production of mesons is valid, then the relationship $\sigma_A \sim A^{2/3}$ must be obtained, independently of the meson energy. These relationships can be obtained in their clearest form in the case of π^0 mesons, which is free of the Coulomb interaction that complicates the interpretation of the results obtained with charged mesons.

Experiments made to study the dependence on A of the photoproduction cross-section for π^0-mesons on complex nuclei,[12-13] carried out by recording π^0 mesons using one of the decay γ quanta, have shown that the relationship $\sigma_A \sim A^{2/3}$ is preserved in the region of complex nuclei at a maximum synchrotron γ-ray beam energy of 265 and 200 Mev. These γ-ray energies correspond to π^0-meson spectra with maxima in the region of 60 and 20 Mev respectively. In the work of Panofsky et al.,[2] the π^0 mesons were recorded using two decay γ quanta. The geometry of the experiment corresponded to recording mesons with energy greater than 100 Mev. However, these experiments can be considered only as preliminary ones, since the results of the work of Panofsky et al.[2] are subject to large error, while the method of recording a π^0 meson by means of only one of its decay γ quanta suffers from certain disadvantages. Firstly, this method does not allow one to determine the energy of the π^0 mesons being recorded. An upper bound on their energy is the maximum energy of the synchrotron γ rays. A reduction of this energy below 200 Mev results in a considerable decrease in the π^0-meson yield, which leads to danger of interference from the background of γ quanta scattered by nuclei, which would be indistinguishable from the effect under observation when such a method of recording mesons is employed. Secondly, the recording of π^0 mesons by means of one of their decay γ quanta requires the knowledge of the angular distribution of mesons produced on nuclei.

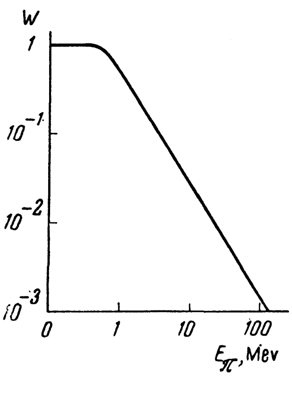

FIG. 1. Energy dependence of the efficiency of recording of π^0 mesons by the measuring equipment.

2. EXPERIMENTAL SETUP

In order to select π^0 mesons of low energy it is necessary to record both the decay γ quanta. In the system of coordinates in which the π^0 meson is at rest the decay γ quanta emerge at an angle of 180° with respect to one another, with the angular distribution of the quanta being isotropic. In the laboratory system the angular distribution of the decay γ quanta from a meson moving with a velocity β is given by

$$P(\alpha)\, d\Omega_\alpha = d\Omega_\alpha / 2\pi\gamma^2 (1 - \beta\cos\alpha)^2, \tag{4}$$

where α is the angle between the direction of motion of the π^0 meson and the direction in which the decay γ quantum is emitted, while $\gamma = 1/\sqrt{1-\beta^2}$. If the angle between the decay γ quanta in the laboratory system is denoted by φ, then

$$\sin(\varphi/2) = (\cos^2\alpha' + \gamma^2 \sin^2\alpha')^{-1/2}. \tag{5}$$

Here α' is the angle of emission of the γ quantum in a system in which the π^0 meson is at rest.

It can be seen thus that corresponding to each value of π^0-meson energy there will exist a minimum angle (critical angle) between the directions of emission of the two decay γ quanta. This angle is determined by the relation

$$\sin(\varphi_k/2) = \gamma^{-1}. \tag{6}$$

Making use of relation (5), we can easily show that the probability that the decay γ quanta are emitted in the laboratory system at an angle φ will be given by

$$p(\varphi)\, d\varphi = \frac{\sin\varphi\, d\varphi}{[(1-\cos\varphi)\gamma^2 - 2]^{1/2}\, \beta\gamma\, (1-\cos\varphi)^{3/2}}\,. \tag{7}$$

This probability has a sharp maximum near the critical angle φ_k determined by relation (6). Thus, the lower limit on the energy of π^0 mesons recorded by means of two γ quanta will be determined by the angle between the detectors of the decay γ quanta. Let us determine the probability of recording mesons of various energies in the case when the angle between the γ-quanta detectors is 180°. If the angle subtended by the detector at the target is φ_D, the apparatus will record π^0 mesons decaying with emission of γ quanta, the angle between which lies within the limits $\pi - \varphi_D \leq \varphi \leq \pi$. Thus, the probability of recording π^0 mesons will be given by:

$$W = \int\limits_{\pi-\varphi_D}^{\pi} P(\varphi)\,d\varphi \Big/ \int\limits_{\varphi_K}^{\pi} P(\varphi)\,d\varphi = 1 - \frac{1}{\beta\gamma}\left[\gamma^2 - \frac{2}{1-\cos(\pi-\varphi_D)}\right]^{1/2}. \qquad (8)$$

The calculated values of W for $\varphi_D = 9°$ and for different π^0-meson energies are plotted in Fig. 1. It can be seen from the graph that the experimental geometry chosen by us allows us to reduce effectively the recording of high energy mesons, without significantly lowering the efficiency for recording slow π^0 mesons.

There exists still another mechanism which reduces the probability of recording by the apparatus of fast π^0 mesons. It is based on the fact that the efficiency of recording of γ quanta by the telescope depends on the γ-quanta energies. When the γ quanta from the decay of a π^0 meson that moves with a velocity β reach both telescopes, one quantum must be moving in the same direction as the π^0-meson, while the other one moves in the opposite direction. In such a case the energy of the former will be given by $h\nu_{\max} = \mu_0 c^2\gamma(1+\beta)/2$, while the energy of the latter will be given by $h\nu_{\min} = \mu_0 c^2\gamma(1-\beta)/2$. Thus, there exists an absolute energy threshold for the recording of π^0 mesons by the apparatus, and the magnitude of this threshold is determined by the threshold energy of the telescope at which the efficiency falls to zero, $\epsilon(h\nu_{\min}) = 0$.

The next section of this article gives the results of measurements of the efficiency of the telescope, which show that its threshold for γ quanta is equal to 35 Mev (Fig. 2). For π^0 mesons this corresponds to an upper threshold of 40 Mev for the apparatus.

The energy spectrum of the π^0 mesons recorded by the apparatus can be determined if we know the energy dependence of the efficiency of recording and the energy spectrum of the π^0 mesons produced in the target. We know the first of these functions. The energy spectrum of the π^0 mesons originating in the target is determined primarily by the momentum distribution of the nucleons in the nucleus. Baldin has carried out calculations[14] of energy spectra of π^0 mesons formed in nuclei through bremsstrahlung. The results of these calculations are in good agreement with available experimental data. Making use of energy spectra obtained by Baldin,[14] we can easily calculate the energy spectrum of π^0 mesons recorded by the apparatus. The spectrum obtained in this manner has a very flat maximum in the range between 1 to 15 Mev; a rapid decrease takes place above 15 Mev.

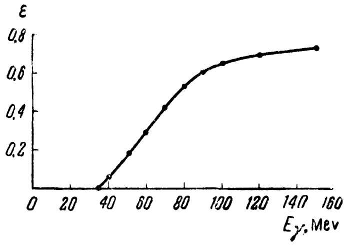

FIG. 2. Efficiency of recording of γ quanta by the telescope.

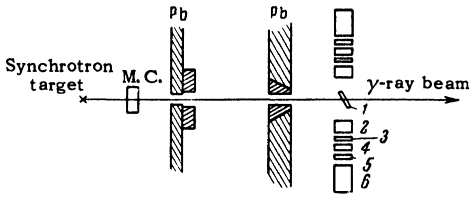

FIG. 3. Experimental geometry. M.C.) monitoring ionization chamber, 1) target, 2) carbon filter, 3) lead converter, 4) scintillator, 5) aluminum absorber, 6) radiator of the Cerenkov counter.

Thus, the recording of π^0 mesons by means of two decay γ quanta first permits us, after making an appropriate choice of geometry, to record mesons of definite energies. Secondly, this method permits us to exclude completely the background of scattered γ quanta. Finally, with the chosen geometry, the apparatus enables us to obtain the total cross section directly without measuring the angular distribution of the mesons, since for slow mesons the probability of emission of decay γ quanta is practically the same in all directions (cf. reference 4).

3. APPARATUS

The measurements were made with the synchrotron of the Physics Institute of the Academy of Sciences, which produces a γ-ray beam with a maximum energy of 265 Mev.

The experimental geometry is shown in Fig. 3. The synchrotron beam passes through a monitor ionization chamber, through two collimators, and falls on the target being investigated. The π^0 mesons formed in the target are recorded by two counter telescopes, each situated at an angle of 90° to the beam on the same straight line passing through the target. The two telescopes are connected for coincidence. Each telescope consists of a carbon filter 6 cm thick, a lead converter 5 mm thick, a scintillation counter, an aluminum absorber 2 cm thick, and a Cerenkov counter. The

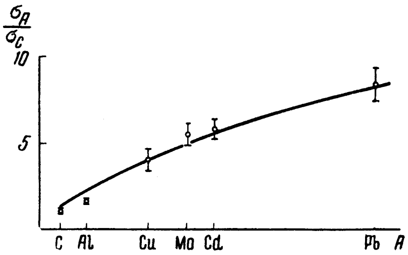

FIG. 4. Results of the measurement of the dependence of the π^0-meson yield on the mass number of the target for maximum energy of the γ-ray beam equal to 265 Mev (circles); the solid curve is $\sigma \sim A^{2/3}$.

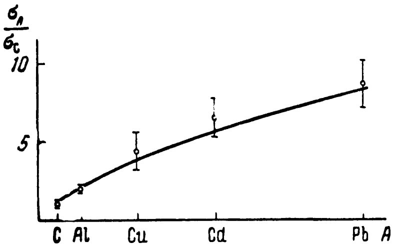

FIG. 5. Results of the measurement of the dependence of the π^0-meson yield on the mass number of the target for maximum energy of the γ-ray beam equal to 210 Mev (circles); the solid curve is $\sigma \sim A^{2/3}$.

carbon filter served to shield the scintillation counter from particles and from the low-energy γ quanta copiously emitted by the target. The scintillator was in the form of a disc 7 cm in diameter and 3 cm thick, and consisted of a solution of terphenyl in toluol (4 g/liter) with addition of a secondary activator. The aluminum absorber served to raise the telescope threshold. The radiator of the Cerenkov counter consisted of a cylindrical vessel 6 cm in diameter and 12 cm long, filled with distilled water. All the counters made use of photomultipliers FEU-33 with improved time characteristics. To reduce the background, the counters were surrounded by lead shields up to 20 cm thick. To decrease the number of accidental coincidences, the duration of the synchrotron pulse was artificially stretched out to 3000 microsec. The intensity of the beam was measured by means of a thin-walled ionization chamber.

When the converters were removed, the counting rate decreased, with the residual counts being determined by the conversion of the γ quanta in the carbon filters and in the scintillators. The targets used in this experiment were situated at an angle of 45° to the γ-ray beam, and were fixed in a device which enabled targets to be changed by remote control. The thickness of each target amounted to 0.1 of a radiation unit. The targets covered the whole beam. To eliminate instabilities, the measurements were carried out using alternately the target investigated and a carbon target, and gave as a result the ratio σ_A/σ_C of the photoproduction cross section for π^0 mesons on the given nucleus to the cross section of production on a carbon nucleus.

The energy dependence of the telescope efficiency was measured by placing the telescope in a beam of monoenergetic electrons. Electrons of a definite energy were selected by means of a magnetic field in which was placed a lead target irradiated by the synchrotron γ-ray beam. Electron-positron pairs were formed in the target.

The range of electron trajectories corresponding to 10% accuracy in determining the electron energy was selected by the current-carrying-filament method. As a measure of efficiency we adopted the ratio of the counting rate of coincidences to the counting rate of pulses of the scintillation counter of a telescope of 100% efficiency. To determine the efficiency of the telescope for γ rays, we measured its efficiency for electrons passing through lead filters of various thicknesses placed in front of the telescope (this corresponds to pair production at various depths within the converter). Using the data received in this manner we calculated the values for the efficiency of the γ telescope. The results are shown in Fig. 2.

4. RESULTS

Measurements of the dependence of the yield of slow π^0 mesons on the mass number were made at maximum γ-ray energies of 265 and 210 Mev. In the case of measurements with $E_\gamma^m = 265$ Mev, we used targets of C, Al, Cu, Mo, Cd, and Pb. The results of these measurements are shown in Fig. 4.

The results of measurements at $E_\gamma^m = 210$ Mev are shown in Fig. 5.

The theoretical curve $\sigma_A \sim A^{2/3}$ in Figs. 4 and 5 was normalized for Pb, with all the experimental points falling on the curve within experimental error in the case of both maximum energies. In the region of light nuclei (C, Al) there is some deviation from the relation $\sigma_A \sim A^{2/3}$, most likely because the number of surface nucleons is not proportional to $A^{2/3}$ in light nuclei.

In order to determine which part of the γ-ray spectrum is responsible for the observed effect, we measured the dependence of the yield of slow mesons on the maximum energy of the γ-ray beam. It can be assumed that the slow π^0 mesons recorded by the apparatus are the result of inelastic scattering of high-energy mesons that originate in the target. If this assumption is correct, the high-energy photons should make an appreciable

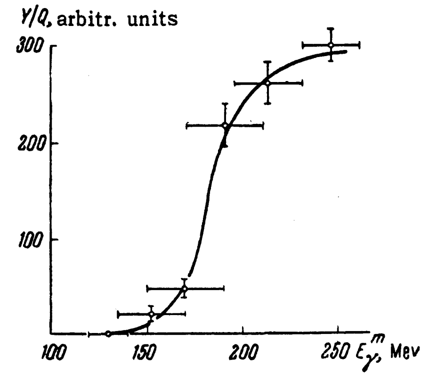

FIG. 6. Dependence of the slow π^0-meson yield in carbon on the maximum energy of the γ-ray beam.

contribution to the effect under investigation. Measurements were made for C and Pb targets, and the results are shown in Figs. 6 and 7 respectively. The quantity Y/Q shown in the graphs is the yield of π^0 mesons per "effective" quantum. The number of "effective" quanta Q is defined as the energy flux in a bremsstrahlung beam divided by the maximum energy E_γ^m. The lack of precision in the maximum energy of the beam is determined by the "stretching" of the duration of the accelerator pulse. As can be seen from the graphs, in the region of high γ-ray energies the yield curve has a plateau which indicates that the contribution of high-energy mesons to the effect being investigated is not significant.

From the curves shown in Figs. 6 and 7 it can be seen that the main contribution to the production of slow π^0 mesons on nuclei is made by γ quanta with energies between 160 to 230 Mev. This agrees with the results of Gorzhevskaia and Panova,[15] who showed that production of a photomeson of low energy (up to 6 Mev) on a nucleus is accompanied by emission of a fast ($E \geq 20$ Mev) recoil nucleon which acquires a considerable fraction of the momentum of the incident γ quantum. Because of this, γ quanta with energies even in excess of 200 Mev participate in the formation of slow π^0 mesons.

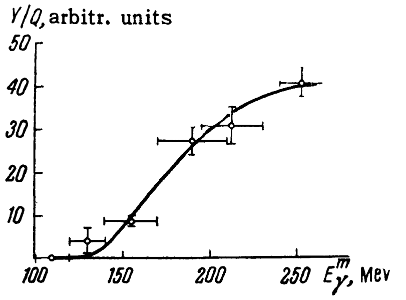

FIG. 7. Dependence of the slow π^0-meson yield in lead on the maximum energy of the γ rays.

In addition to the inelastic scattering of high-energy mesons, a definite contribution to the effect recorded may also come from scattering events accompanied by charge exchange of low-energy $\pi^\pm$ mesons. However, available experimental data on scattering of $\pi^\pm$-mesons on nuclei accompanied by charge exchange[16,17] show that the mean free path for scattering accompanied by charge exchange of charged π mesons in nuclear matter amounts to $\sim 100 r_0$ for meson energies from 30 to 50 Mev, and increases rapidly with decreasing meson energy. Thus, in the case of mesons of energy ~ 10 Mev, we can practically neglect scattering accompanied by charge exchange. Moreover, if a significant contribution is made by the scattering accompanied by charge exchange of charged π-mesons, the dependence of the yield of slow π^0 mesons on A must be stronger than $A^{2/3}$, since all the nucleons in the nucleus participate in the scattering.

Thus, experimental results show that the cross-section for the photoproduction of slow π^0 mesons increases in proportion to the $2/3$ power of the mass number of the target nuclei, i.e., proportionally to the nuclear surface. The same dependence of the photoproduction cross-section on the mass number was obtained by Popova, Semashko, and Iagudina for low energy π^- mesons.[18]

To be able to draw a final conclusion regarding the mechanism of photoproduction of π mesons on complex nuclei, it is necessary to investigate in greater detail the processes of interaction of mesons with nuclear matter and to make a quantitative estimate of the magnitude of the mean free path λ_a for mesons of definite energies in nuclei. An estimate of the value of the absorption mean free path of slow π mesons in nuclear matter can be made on the basis of the following considerations:

1. The principal process of interaction between a π meson and the nucleus is absorption by a pair of nucleons (two-nucleon absorption).

2. The two-nucleon absorption cross section for a π meson in the nucleus can be related to the absorption cross section for π mesons in deuterium by means of the following formula:

$$\sigma_\pi = \Gamma\sigma(\pi^+ + d \to p + p). \tag{9}$$

In the reaction $\pi^+ + d \to p + p$, the absorption of a meson by a pair of nucleons, which acquire in the final state an energy on the order μc^2, takes place when the distance between the latter is reduced to an order of $\hbar/\mu c$. The coefficient Γ in formula (9) represents the ratio of the probabilities that two nucleons are $\hbar/\mu c$ apart in the nucleus and in the deuteron and, consequently, depends on meson energy. However, it is clear that for low π-meson kinetic energies, when $E_{\pi} \ll \mu_0 c^2$, the quantity Γ must be constant. According to the calculations of Wilson[9] and Levinger,[10] and also from the analysis of experimental data of Byers,[19] Tenney and Tinlot,[20] and Byfield et al.,[21] $\Gamma = 5$ to 6 in the region of small π-meson energies.

3. The quantity $\sigma(\pi^+ + d \rightarrow p + p)$ can be obtained from experiments on the absorption of π mesons in deuterium, and also by utilizing the principle of detailed balancing from the cross section of the inverse reaction $p + p \rightarrow \pi^+ + d$. It can be easily seen that

$$\sigma(\pi^+ + d \rightarrow p + p) = \frac{2}{3}\frac{M}{\mu}\left(\frac{1}{\eta}\right)^2 \sigma(p + p \rightarrow \pi^+ + d). \tag{10}$$

Here $\eta = p_{\pi}/\mu c$ is the momentum of the π meson in units of μc, while M and μ are the masses of the nucleon and the π meson respectively.

The energy dependence of the cross section of the reaction $p + p \rightarrow \pi^+ + d$ is derived from semi-empirical considerations. It is shown by Rosenfeld[22] and Gell-Mann and Watson[23] that

$$\sigma(p + p \rightarrow \pi^+ + d) = (0.14\eta + 1.0\eta^3)\cdot 10^{-27}\ \text{cm}^2. \tag{11}$$

Frank et al.[24] have made calculations utilizing relations (9) to (11), and they have shown that the mean free path λ_a for the absorption of a π meson in nuclear matter increases as the π-meson energy is decreased right down to 30 Mev. In the energy region from 30 down to 2 Mev, $\lambda_a \approx 10r_0$ and is almost independent of the meson energy. At energies less than 2 Mev, λ_a decreases in proportion to the π-meson momentum. However, these calculations were made for charged π mesons. In the case of π^0 mesons the absorption is due to the reaction $\pi^0 + d \rightarrow n + p$. The cross section of this reaction is only half of the cross section of the reaction $\pi^+ + d \rightarrow p + p$, since the isotopic spin of the n-p system may be equal to 0 and 1 with equal probability, while the isotopic spin of the p-p system is equal to 1. The transition $I = 0 \rightarrow I = 1$ takes place when a meson is absorbed, while the transition $I = 0 \rightarrow I = 0$ is forbidden. Thus, only half of the possible final states of the nucleons participate in the π^0-meson absorption reaction, and the value of the mean free path of π^0 mesons in the nucleus will be approximately $20r_0$ in the energy range from 2 to 30 Mev, i.e., practically for all mesons recorded in the present work.

5. CONCLUSION

Present experiments on the study of the dependence of the cross section of photoproduction of slow ($E_{\pi} \sim 10$ Mev) π^0 mesons on the mass number of the nucleus have shown that the cross section for this process is proportional to $A^{2/3}$. On the other hand, an analysis of the absorption of slow π^0 mesons in nuclei leads to the conclusion that the mean free path for absorption of mesons of this energy in the nucleus amounts to $20r_0$, i.e., all nuclei right up to the heaviest ones must be transparent for such mesons. Consequently the experimentally obtained dependence cannot be explained by the absorption of all mesons formed inside the nucleus, as is done in the description of the process of photoproduction of mesons from the point of view of the optical model.[6] The results obtained support the theory of surface production of π mesons on nuclei,[8,9] according to which real mesons are produced only on the surface of nuclei.

When a γ quantum is absorbed by a nucleon situated inside a nucleus, photodisintegration of this nucleus takes place, whereby the photon energy is transmitted to a pair of nucleons, with the probability of such photodisintegration being greater than the probability of π-meson photoproduction.

The electronic apparatus utilized in the present experiment was constructed and built by engineers P. N. Shareiko and A. A. Rudenko, to whom the authors wish to express their sincere gratitude.

In conclusion we take this opportunity to express our gratitude to Prof. V. I. Veksler and to Prof. P. A. Cerenkov for their interest in our work and for a number of valuable suggestions, to A. D. Makov who participated in the preparation and the performance of the experiment, and also to the members of the accelerator crew for looking after the operation of the synchrotron.

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[1] R. M. Littauer and D. Walker, Phys. Rev. **86**, 838 (1952).

[2] Panofsky, Steinberger, and Steller, Phys. Rev. **86**, 180 (1952).

[3] Anderson, Kenney, and McDonald, Phys. Rev. **100**, 1798 (1955).

[4] Williams, Crowe, and Friedman, Phys. Rev. **105**, 1840 (1957).

[5] Imhof, Knapp, Easterbey, and Perez-Mendez, Phys. Rev. **108**, 1040 (1957).

[6] Brueckner, Serber, and Watson, Phys. Rev. **84**, 258 (1951).

[7] D. H. Stork, Phys. Rev. **93**, 868 (1954).

[8] S. T. Butler, Phys. Rev. **87**, 1117 (1952).
[9] R. R. Wilson, Phys. Rev. **86**, 125 (1952).
[10] J. S. Levinger, Phys. Rev. **84**, 43 (1951).
[11] Odian, Stein, Wattenberg, et al., Phys. Rev. **102**, 837 (1956).
[12] Belousov, Tamm, and Shitov, Dokl. Akad. Nauk SSSR **112**, 1017 (1957), Soviet Phys. "Doklady" **2**, 90 (1957).
[13] Govorkov, Gol'danskii et al., Dokl. Akad. Nauk SSSR **112**, 37 (1957), Soviet Phys. "Doklady" **2**, 4 (1957).
[14] A. M. Baldin, Thesis, Phys. Inst., Academy of Sciences, U.S.S.R., 1951.
[15] E. G. Gorzhevskaia and N. M. Panova, Dokl. Akad. Nauk SSSR **111**, 1205 (1956), Soviet Phys. "Doklady" **1**, 757 (1956).
[16] W. J. Spry, Phys. Rev. **95**, 1299 (1954).
[17] G. Saphir, Phys. Rev. **104**, 535 (1956).
[18] Belousov, Popova, Semashko, Shitov, Tamm, Veksler, and Jagudina, Proc. CERN Symposium **2**, 288 (1956).
[19] N. Byers, Phys. Rev. **107**, 843 (1957).
[20] F. H. Tenney and J. Tinlot, Phys. Rev. **92**, 974 (1953).
[21] Byfield, Kessler, and Ledermann, Phys. Rev. **86**, 17 (1952).
[22] A. Rosenfeld, Phys. Rev. **96**, 139 (1954).
[23] M. Gell-Mann and K. M. Watson, Ann. Rev. Nucl. Sci. **4**, 219 (1954) [transl. in Usp. Fiz. Nauk **59**, 399 (1954)].
[24] Frank, Gamel, and Watson, Phys. Rev. **101**, 891 (1956).

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INVESTIGATION OF RELAXATION PROCESSES IN A SERIES OF FLUORINE COMPOUNDS OF CARBON

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A study is made of the influence of anisotropy of the chemical shift tensor on the relaxation time of fluorine nuclei. It is found that the difference in relaxation times of fluorine nuclei and of protons in one and the same molecule depends on the presence of nuclei of another halogen.

FLUORINE is one of the most electronegative elements. The methods of nuclear magnetic resonance are currently applied successfully to the investigation of fluorine compounds. These investigations are devoted chiefly to the fine structure of the fluorine resonances, and also to the study of relaxation processes. Gutowsky and Hoffman[1,2] examined nuclear magnetic screening of hydrogen fluoride and of a large number of other inorganic fluorides. A considerable number of aromatic fluoride compounds have been studied by Borodin and Skripov.[3,4] Gutowsky and Woessner[5] measured relaxation times in a series of fluorocarbons. They found that protons have considerably longer relaxation times than do fluorine nuclei in the same molecule. The maximum value of the ratio $R = T_1(H^1)/T_1(F^{19})$ came to 9.2, in connection with which the authors emphasized the dependence of the given ratio on the strength of the magnetic field. They also express the hypothesis that fluctuations in the screening field, stipulated by the anisotropy of the chemical shift tensor, add a contribution to the relaxation time of the fluorine. On superimposing a constant magnetic field H_0 on the specimen, the molecular electrons undergo a precession, by virtue of which an additional field $-\sigma H_0$ arises, proportional but opposite to the applied field, σ (σ is a constant that characterizes the degree of screening of the nucleus by the electrons). In the general case, σ is represented by