SOVIET PHYSICS

JETP

A translation of the Journal of Experimental and Theoretical Physics of the USSR.

SOVIET PHYSICS JETP   Vol. 6(33), No. 2, pp 245-436   February, 1958

*PRODUCTION OF NEUTRAL π-MESONS IN VARIOUS NUCLEI BY 260-660 MEV PROTONS**

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Submitted to JETP editor February 27, 1957

J. Exptl. Theoret. Phys. (U.S.S.R.) 33, 313-319 (August, 1957)

The γ-ray yields from the decay of π^0-mesons produced by 260-660 Mev protons in complex nuclei were measured at various angles. The total cross sections for production of π^0-mesons in various nuclei were determined in this energy range.

THE study of processes of production of π^0-mesons in complex nuclei is a natural source of information about their interaction with nuclear matter. This is connected with the fact that, owing to the short life of π^0-mesons in nuclear matter, it is possible to study their interaction with only the nucleons of that nucleus in which they are produced. The results of similar experiments in photoproduction of mesons are much easier to interpret. In the case of bombardment of the nucleus by nucleons the general picture of the phenomena becomes much more complicated, owing to the strong interaction of the incident nucleons with nuclear matter.

In the present work, carried out on the six-meter phasotron of the Joint Institute for Nuclear Research, the yields of γ-rays from the decay of π^0-mesons produced in complex nuclei by protons were measured at various angles. The energy of the protons was varied from 260 to 660 Mev.

METHOD OF MEASUREMENT

The beam of γ-rays from the decay of π^0-mesons produced in the internal target of the accelerator was measured using the telescope described in Ref. 1. The number of protons going through the target was determined by the ionization heating of the target. The arrangement of the experiment and the method of measurement of the absolute cross sections used in the present work were essentially the same as previously described.[1] Therefore we restrict ourselves here to considering only the additional methodological problem connected with measurement of the ratios of differential cross sections for different nuclei.

The differential cross section for γ-ray production is given by the formula

$$d\sigma_A^\gamma / d\Omega = n\varepsilon (1 + \varepsilon_{\text{star}} / \varepsilon)(1 + \delta) A / m F_\gamma \Omega N. \quad (1)$$

Here n is the number of γ-rays counted by the telescope per unit time, m is the heat current through the target measured by a thermocouple, F_γ is the efficiency of the γ-telescope, ϵ is the specific ionization loss (for 1 g/cm^2), ϵ_{star} is the heat produced in the target because of star-production, δ is a small correction taking account of the absorption of γ-rays in the target and in air, Ω is the solid angle of counting, A the atomic number of the target material, and N is Avogadro's number. In this work we measured the ratios of the cross sections for various elements to those for carbon (relative cross sections).

*The results of the present work were reported at the conferences in Moscow (May, 1956) and Geneva (June, 1956).

As the measurements showed, for fixed proton energy and angle of γ-ray counting, the efficiency of the γ-telescope did not depend on the material of the irradiated target. Therefore the relative cross sections were determined by the simple relation:

$$(d\sigma_A^\gamma / d\Omega)' = (n/m)' (1 + \varepsilon_{star}/\varepsilon)' (1 + \delta)' (A\varepsilon)'. \quad (2)$$

Here, for conciseness, the prime indicates that the quantities occurring in the formula relating to atomic weight A are divided by the corresponding quantities obtained for carbon. The quantities $(1 + \epsilon_{star}/\epsilon)'$ and $(1 + \delta)'$ constitute small corrections. They are given in Table I. The thickness of the targets used varied from element to element, constituting, on the average, about 1 g/cm^3.

TABLE I

Element	$(1+\delta)'$	$(1+\varepsilon/\varepsilon_{star})'$ calculated	$(1+\varepsilon/\varepsilon_{star})'$ exper.
Li_6	1.00	1.01	
Li_7	1.00	1.01	
Be	1.00	1.00	
C	1.00	1.00	1.00
Al	1.01	1.03	1.04±0.03
Cu	1.02	1.03	
Cd, Sn	1.04	1.04	
Pb	1.06	1.05	1.06±0.03
U	1.08	1.05	

The second column of the table gives corrections calculated to an accuracy of 1 — 2% on the basis of the spectra of the particle-ray stars measured by Grigor'ev and Solov'eva.[2] An experimental determination of the ratio $(1 + \epsilon_{star}/\epsilon)'$ was also attempted. For this, targets prepared from graphite, aluminum and lead were placed in a magnetic channel of the phasotron and irradiated by the proton beam. A very sensitive small-gauge thermopile (of sensitivity 3×10^{11} Mev/sec.mv) containing 300 copper-constantan thermocouples was used to measure the small heat current through the target. The relative proton currents through the targets were determined in these experiments by the activation of thin copper foils. It should be noted that a similar experiment cannot be carried out on the internal circulating beam of the accelerator because in this case the method of activation of the foil does not furnish the necessary high accuracy of measurement of the relative proton beams through the target. Because the intensity of the extracted beam is small in comparison with the internal beam, it was necessary to use thick targets ($\approx$ 1 cm). Because of this the time of establishing thermal equilibrium was large ($\approx$ 1 hr) which restricted the possibilities of accurate measurement. The results of measurement are given in Table I (final column).

INVESTIGATION OF THE ANGULAR DISTRIBUTION OF γ-RAYS

The measurements made earlier[3] showed that the relative cross sections for production of γ-rays at zero angle grew with increasing atomic weight sustantially more slowly than at 180°. This means that the angular distribution of π^0-mesons depends substantially on the atomic weight of the target material and, consequently, in order to obtain the values of the total cross sections for production of π^0-mesons in various elements, it is necessary to have information about the angular distributions of the γ-rays.

In the present work the γ-ray yields were measured in the angular intervals 0 — 33° and 147 — 180° in the laboratory system (l.s.). In Table II the results of these measurements, carried out for a proton energy of 660 Mev, are given in the effective center-of-mass system (c.m.s.) of the colliding nucleons.

The velocity $\bar{\beta}_c$ = 0.50 of the effective c.m.s. was found by averaging the velocities of the c.m.s. of the colliding nucleons under the assumption that the momentum distribution of the nucleons in the nucleus is Gaussian with standard deviation 120 Mev/c (corresponding to an energy of 8 Mev) cut off at 22 Mev. The quantity $\bar{\beta}_c$ is insensitive to the form of the momentum distribution for a proton energy of 660 Mev. Thus, if a Fermi distribution with Fermi energy 22 Mev is taken for the nucleons in the nucleus, then $\bar{\beta}_c$ = 0.48. These values of $\bar{\beta}_c$ are not very different from the velocity of the c.m.s. for the case of collision with a nucleon at rest (β_c = 0.52).

Since the velocity of the π^0-mesons is near to that of light, the angular distributions of γ-rays practically coincide with the angular distributions of the π^0-mesons from whose decay they arise.

The decrease in the relative small-angle yields of π^0-mesons with increasing atomic weight can be explained by the fact that in this case mainly γ-rays are registered from the decay of π^0-mesons produced in that part of the atom which is screened from the bombarding protons by the nucleons. In going through the nucleus, the protons lose energy in collisions with nucleons of the nucleus and do not take part in the process of meson production. With increasing atomic weight the screening, naturally, increases. As the angle of observation increases, the effect of screening weakens, as can be seen from Table II.

In the lightest elements the lack of transparency for protons and the absorption of mesons appear to be comparatively weak. From Table II it can be seen that the angular distribution of γ-rays for these nuclei

TABLE II

ϑ° c.m.s.	0	35	55	160	169	180
Li_6	0.80±0.04	—	0.91±0.03	1.00±0.07	—	1.00±0.04
Li_7	0.74±0.03	—	0.82±0.03	1.00±0.06	0.96±0.10	1.00±0.04
Be	0.70±0.02	—	0.80±0.04	1.10±0.07	—	1.00±0.03
C	0.61±0.02	0.63±0.04	0.68±0.03	1.02±0.05	0.95±0.07	1.00±0.02
Al	0.50±0.02	—	0.58±0.04	0.97±0.06	—	1.00±0.03
Cu	0.37±0.02	—	0.48±0.03	0.92±0.07	—	1.00±0.03
Cd, Sn	0.31±0.01	—	0.42±0.04		—	1.00±0.03
Pb	0.29±0.01	—	0.38±0.02	0.95±0.04	—	1.00±0.03

corrected for the small effect of screening are practically isotropic. From this it is possible to draw the conclusion that the angular distribution of π^0-mesons produced at 660 Mev in proton-nucleon collisions are nearly isotropic. This agrees with other data.[1,4]

In order to find out how the angular distribution of π^0-mesons changed with decreasing the energy in the nucleon collisions, relative yields of γ-rays for angles of 33 and 147° in the l.s. for lithium were compared for various proton energies. The changes demonstrated that the anisotropy of the π^0-meson angular distribution grew with decreasing energy. If the π^0-mesons produced in p-n collisions at 450 Mev are taken to be distributed as $1/3 + b\cos^2\vartheta$, then it follows from our measurements that $b \geq 0.5 \pm 0.2$. This result agrees with the data obtained by studying γ-ray spectra.[4] Deviations of the π^0-meson angular distribution from isotropy become noticeable for energies below 550 Mev.

The change in relative yields of γ-rays for the angles noted above also continues for energies below 400 Mev. However, a quantitative interpretation of these measurements is not possible in practice because here the yields depend very essentially on assumptions about the character of the momentum distribution of nucleons in the nucleus, and about the spectrum of π^0-mesons.

DEPENDENCE OF THE DIFFERENTIAL CROSS SECTIONS FOR PROTONS OF VARIOUS ENERGIES ON ATOMIC WEIGHT

The dependence of the differential cross sections for γ-ray production on the atomic weight of the target material was measured for proton energies of 260, 340, 445 and 660 Mev at two angles. In varying the energy the angles changed somewhat, being 33 and 147° (l.s.) at 660 Mev and 40 and 140° at 260 Mev. The relative cross sections obtained are given in Table III (angles 33 — 40°) and Table IV (angles 147 — 140°).

TABLE III

E_p(Mev)	660	445	340	260
D*	0.48±0.05	0.30±0.06	—	—
Li_6	0.70±0.15	0.75±0.15	—	—
Li_7	0.89±0.02	0.88±0.02	0.72±0.03	0.72±0.03
Be	0.95±0.03	0.88±0.03	0.85±0.05	0.77±0.04
C	1.00	1.00	1.00	1.00
Al	1.48±0.04	1.52±0.04	1.67±0.07	1.82±0.11
Cu	2.3 ±0.1	2.8 ±0.2	2.9 ±0.1	3.5 ±0.2
Sn	3.2 ±0.1	3.8 ±0.1	4.0 ±0.2	4.9 ±0.3
Pb	4.2 ±0.1	5.0 ±0.2	5.7 ±0.3	6.3 ±0.2
U	4.1 ±0.3	5.2±0.3	—	—

*Taken from Ref. 1.

The angular distribution of the π^0-mesons ($F_\pi(\vartheta)$) and that of the γ-rays produced in their decay ($F_\gamma(\vartheta)$) are connected by the integral relation

$$F_\gamma(\vartheta) = \int_{-1}^{+1} F_\pi(\vartheta_0)\, G(\beta, \cos\vartheta, \cos\vartheta_0)\, d\cos\vartheta_0. \quad (3)$$

Here β is the velocity of the π^0-meson,

$$G(\beta, \cos\vartheta, \cos\vartheta_0) = {}^1/_2\, \gamma^{-2}(1 - \beta\cos\vartheta\cos\vartheta_0) \times$$
$$\times\ [(\beta\cos\vartheta_0 - \cos\vartheta)^2 + \sin^2\vartheta/\gamma^2]^{-3/2},\quad \gamma^2 = 1/(1-\beta^2).$$

Equation (3) shows that the angular distribution $F_\gamma(\vartheta)$ differs slightly from $F_\pi(\vartheta)$ only for $\beta \gtrsim 0.9$. The degree of anisotropy in the distribution $F_\gamma(\vartheta)$ decreases rapidly with decreasing β. Thus, even if the angular distribution of π^0-mesons does not change with decreasing proton energy, owing to the decrease in velocity of the π^0-mesons, the difference between the angular distributions of the γ-rays, which occur for light and heavy nuclei for energies of 450 — 660 Mev, should vanish as the threshold for meson production is approached. Therefore, with decreasing proton energy the relative cross sections measured at 33° for heavy nuclei should increase, and at 147°, decrease. As can be seen from Tables III and IV, this drawing together of the values of the relative cross section really does occur; however, simultaneously with this, the relative cross sections at 147° not only does not decrease, but even systematically grows as the threshold for meson production is approached. This indicates that the angular distribution of π^0-mesons changes in the energy interval 260 — 660 Mev. The latter may be connected with a diminishing of the already discussed effect of screening, brought about by the decrease in the meson production cross section. A quantitative evaluation of this change in angular distribution of π^0-mesons, which requires extensive calculation (for example, by

TABLE IV

E_p (Mev)	660	445	340	340**	260
D*	0.30±0.05	0.20±0.05	—	0.143±0.004	
Li_6	0.50±0.10	0.55±0.10	—	—	—
Li_7	0.75±0.01	0.75±0.02	0.64±0.02	0.57±0.02	0.55±0.02
Be	0.83±0.03	0.79±0.03	0.82±0.04	0.83±0.02	0.74±0.03
C	1.00	1.00	1.00	1.00	1.00
Al	1.70±0.04	1.84±0.03	1.96±0.06	2.1±0.1	1.9±0.1
Cu	2.9 ±0.1	3.6 ±0.1	4.2 ±0.2	4.2±0.2	—
Cd	4.6 ±0.1	5.7 ±0.2	6.4 ±0.3	—	—
Pb	7.1 ±0.2	8.2 ±0.4	9.6 ±0.5	7.8±0.4	9.4±0.5
U	6.6 ±0.6	—	—	—	—

*Taken from Ref. 1.

**Taken, for comparison, from Ref. 5, where the measurements were carried out at 135° in the l.s.

the Monte Carlo method), has not been carried out in the present work.

Comparison of results for measurements of the dependence of the yield of charged mesons on atomic weight with the data on the absorption of π^0-mesons in nuclei allowed several authors[6,7] to conclude that there is a substantial decrease in the probability of π-meson production for the strongly bound nucleons in the interior of the nucleus. Elucidation of the analogous problem in the production of π-mesons by nucleons is also of considerable interest. However, the strong interaction of the incident nucleons with nuclear matter already discussed, leads by itself to the situation in medium and heavy nuclei where the π-mesons are effectively produced only in the surface of the target nucleus. If a decrease in the probability of π-meson production inside the nucleus really does take place, then this should be reflected in the behavior of the relative cross sections only in the region of light nuclei, and only in the case when the absorption of the π-mesons leaving the nucleus is small. In connection with this, a definitive answer to the question about the existence of a supplementary mechanism which diminishes the probability of meson production by protons on the strongly bound nucleons inside the nucleus is possible only after carrying out calculations which take the absorption of protons and mesons in light nuclei correctly into account. However, the existence of models of the complex nucleus which could be used to solve this problem, have a sufficiently reliable basis only for the case of heavy nuclei. Therefore, from the presently-available experimental data on the production fo π^0-mesons in light nuclei (Refs. 3, 5, 8 and this work) the relative probabilities of π^0-meson production in the surface and on the internal nucleons of the nucleus cannot be determined.

DEPENDENCE OF THE TOTAL CROSS SECTIONS ON THE PROTON ENERGY

Using the data about the γ-ray angular distribution given in Table I, and the value of the absolute differential cross section determined for energy 660 Mev in the work of Ref. 1, we find that the total cross section for production of π^0-mesons by 660 Mev protons on carbon is

$$\sigma_C^{\pi^0} = (28 \pm 3) \cdot 10^{-27}\ \text{cm}^2.$$

The total cross sections for other elements are given in Fig. 1.

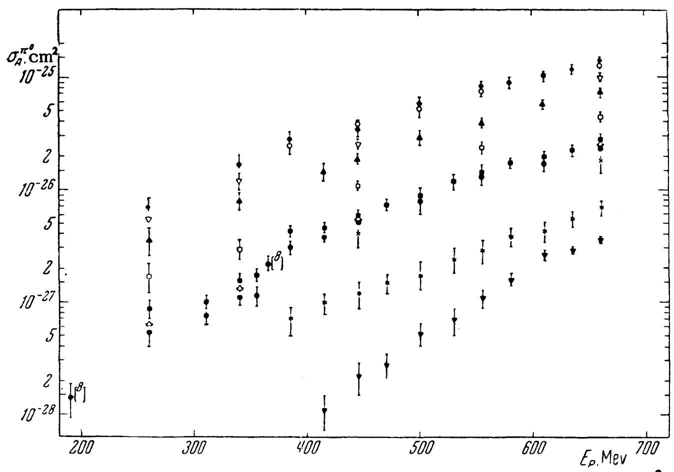

FIG. 1. Total cross sections for production of π^0-mesons by protons on various nuclei ○ — U, ◆ — Pb, ∇ — Cd, Sn, ▲ — Cu, □ — Al, ■ — C, Δ — Be, ● — Li_7, × — Li_6, ✶ — D (from Ref. 1), ▼ — H(from Ref. 1).

The dependence of the total cross section on energy was measured for a series of elements (see Fig. 1). In these experiments the variation in proton energy was achieved by inserting targets at different distances from the center of the accelerator; γ-rays were counted at angles 33 and 147°. The change in angular distribution of the π^0-mesons was taken into account in the determination of the value of the total cross sections.

As was pointed out above, the change in angular distribution of the π^0-mesons connected with the effects of screening and absorption was small in the case of the lightest nuclei. This permits the analysis of the energy dependence of the total cross section obtained for a light element (lithium) to be carried out without taking into account the change in transparency of the nucleus. Comparison of the energy dependence of the total cross section measured near the threshold for meson production with calculated curves permits us to draw (in the framework of the impulse approximation) several conclusions about the character of the energy distribution of nucleons in the nucleus since the behavior of the calculated curves in this energy region is, in large part, determined by the form of the energy distribution of the nucleons. The excitation function is given (in relative units) in Fig. 2, together with curves calculated in the impulse approximation for the case of a Gaussian distribution of nucleons in the nucleus with standard deviation 120 Mev/c (nucleon energy 8 Mev), cut off at an energy of 22 Mev. The Pauli Principle was not taken into account in the calculation since the nucleon energies after meson production substantially exceeded the Fermi energy. The divergence of the energy dependencies of the cross section from the calculated curves serves to indicate that there should be more high energies in the energy spectrum of the nucleons inside the nucleus than occur in the Gaussian distribution taken.

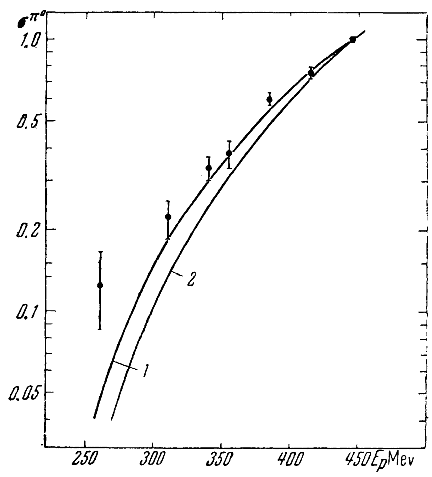

FIG. 2. Energy dependence of the cross section for production of π^0-mesons in lithium near threshold. Curve 1 corresponds to the dependence of the cross section production of π^0-mesons in collisions of the incident protons with nucleons in the nucleus: $\sigma\pi^0 \sim p_{max}^3$; curve 2 was calculated for the case $\sigma\pi^0 \sim p_{max}^4$, where p_{max} is the maximum momentum of the π^0-meson in the c.m.s. of the colliding nucleons.

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Translated by G. E. Brown
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