MEASUREMENT OF THE NEUTRAL PION LIFETIME

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To determine the lifetime of neutral pions (τ_{π^0}) by the Primakoff method, the angular distribution of π^0 mesons produced by 1.1-GeV γ quanta in the Coulomb field of a lead nucleus is measured. An analysis of the data yields $\tau_{\pi^0} = (0.90 \pm 0.068) \times 10^{-16}$ sec.

INTRODUCTION

THE work that has been done on the measurement of the π^0-meson lifetime was stimulated by both the fundamental importance of this lifetime and its interest in connection with the electromagnetic decay of particles. Direct methods (such as measuring the distribution of Dalitz conversion pairs from π^0 mesons) have yielded $\tau_{\pi^0} \sim 1.5 \times 10^{-16}$ sec, which because of large errors was regarded as the upper limit of τ_{π^0}. On the other hand, Primakoff[1] has suggested an indirect method of measuring τ_{π^0}, utilizing its relation to the cross section for π^0 photoproduction in the Coulomb fields of heavy nuclei. This method, while in principle permitting us to determine τ_{π^0} very accurately, encounters experimental difficulties. Mesons produced in the Coulomb field of a nucleus move in directions that form very small angles with the bremsstrahlung beam. In addition, the analysis of the experimental data is complicated by the fact that Coulomb production is accompanied by the other processes whereby neutral pions are usually produced on nuclei.

The π^0 lifetime was determined by the Primakoff method in[2-5], where neutral pions were registered through their two decay γ quanta by means of total-absorption Cerenkov counters, thus limiting the accuracy of the γ-ray angle measurements. Therefore in those investigations where the angular resolution was small, only the mere occurrence of the given effect was indicated. In[4] the angular resolution was reduced to 0.5°, which is practically the limit for this technique, and the measured angular distribution of the mesons for the first time permitted a more accurate value of τ_{π^0} than that obtained by the direct methods.

EXPERIMENT

It was our purpose in the present work to investigate π^0 photoproduction in the Coulomb field of a nucleus (the Primakoff effect) in order to determine τ_{π^0}; preliminary results have been published in[6]. The angular resolution was improved considerably by the use of shower spark chambers. The work was done with the aid of the electron synchrotron "Sirius."

The experimental scheme is shown in Fig. 1. The bremsstrahlung beam, of maximum energy 1.1 GeV, was collimated to a 1-mm diameter and was magnetically cleared of charged particles. The beam then struck a lead target 0.1 mm thick and was monitored with a Wilson quantameter that determined doses to within

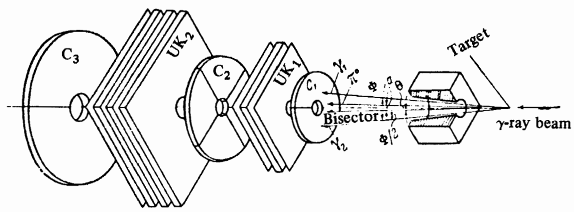

FIG. 1. Experimental scheme.

±2%. The decay γ rays were registered with apparatus, described in[7], that consisted of eight scintillation counter and two shower spark chambers. The counters and spark chambers were placed along the axis of the beam, which passed through apertures in the scintillators and spark chambers. The openings in the outside plates of the spark chambers were sealed with Mylar film in order to reduce the background.

The scintillator counters were connected in three groups. The first group C_1 was connected in anticoincidence with the other groups for the purpose of excluding charged particles emitted by the target. Counter groups C_2 and C_3 were connected in coincidence to register electrons (from conversion γ rays) that were emitted from the central plate of the spark chamber SC_1. With the arrival of two simultaneous pulses from C_2 and C_3 the coincidence scheme triggered the spark chambers. Both spark chambers were projected through a system of mirrors for recording with a motion picture camera; about 60 000 photographs were obtained.

In scanning the motion picture film we selected frames showing no tracks in the first gap of SC_1 but two tracks in the second gap, while SC_2 showed two showers, each corresponding to at least 400 MeV. The energy was evaluated by means of a calibration curve obtained from preliminary measurements with a magnetic spectrometer. From the track coordinates in the second gap of SC_1 we determined the divergence angle Φ and the angle between the bremsstrahlung axis and the bisector of Φ. Assuming a point target, we determined Φ with $\pm 3'$ accuracy.

The high counting rates in the scintillation counters, resulting from the fact that the instruments were very close to the bremsstrahlung beam, induced spurious triggering of the spark chambers. In addition, on the path from the target to SC_1 the bremsstrahlung beam generated charged particles that passed through the aperture in counter group C_1 and triggered C_2 and C_3. All these cases were easily identified during scanning and were eliminated. Most of the background represented double pion production on nuclei. Two decay γ quanta from different mesons can completely simulate Coulomb pion production. The only difference consists in the fact that γ quanta from different mesons are not correlated and their divergence angle Φ is distributed uniformly from 0° to 180°. The divergence angle of decay γ quanta from single mesons has the distribution

$$\frac{dn}{d\Phi}=\frac{1}{2\gamma^2\beta}\frac{\cos(\Phi/2)}{\sin^2(\Phi/2)\sqrt{\beta^2-\cos^2(\Phi/2)}} \quad (1)$$

where β is the π^0 velocity and $\gamma = 1/\sqrt{1-\beta^2}$. Therefore Φ varies from a minimum, given by

$$\sin(\Phi_{min}/2)=\mu_{\pi^0}/E_{\pi^0}, \quad (2)$$

to 180°. We thus see that in the general case exact knowledge of Φ without measurement of the decay γ-ray energies will not suffice for determining the direction of π^0 flight. Since the shower chambers permit only an evaluation of photon energies, two methods were considered for going from the distribution of the bisectors to the meson distribution:

1. The selection of events with divergence angles from Φ_{min} to $\Phi_{min}+\delta$, where Φ_{min} is determined from the maximum bremsstrahlung energy and δ represents the accuracy with which the divergence angles of the decay γ quanta are measured. In this case the accuracy of π^0 direction measurements is given by

$$\cos\alpha=\cos\left(\frac{\Phi_{min}+\delta}{2}\right)\sqrt{1+\left(\frac{\mu_{\pi^0}}{p_{1/2}}\right)^2} \quad (3)$$

where α is the deviation of the bisector from the pion direction, and

$$p_{1/2}\approx 2p_{min}p_{max}/\sqrt{3p_{max}^2+p_{min}^2}. \quad (4)$$

Here p_{min} and p_{max} are the minimum and maximum momenta of pions whose decay γ quanta are in the angular range from Φ_{min} to $\Phi_{min}+\delta$.

To calculate the number of mesons whose trajectories deviate from the bisector by angles ranging from 0° to α, we use

$$n=\sin\alpha/\sqrt{1-\beta^2\cos^2\alpha}. \quad (5)$$

For our apparatus $\alpha = 20'$; thus we have $n \sim 10\%$ for "quasisymmetric" decays. Therefore the basic deficiency of this method consists in the small fraction of events that are suitable for analysis as compared with the total number of registered decays.

2. The method described by Richards in[8]. Here we must know the energy of the incident γ quanta. The bremsstrahlung beam has a continuous spectrum, and it is necessary to work with two values of the maximum beam energy, so that the difference spectrum will correspond to a fixed energy interval of the γ quanta striking the target.

Since preliminary investigations showed that in work with the bremsstrahlung beam the second method is more laborious and leads to great ambiguities, our measurements were obtained mainly at 1.1 GeV and in scanning the film we selected only the "quasisymmetric" decays with divergence angles satisfying (2).

The functions of Φ are very sensitive to the maximum bremsstrahlung energy. Figure 2 shows the very

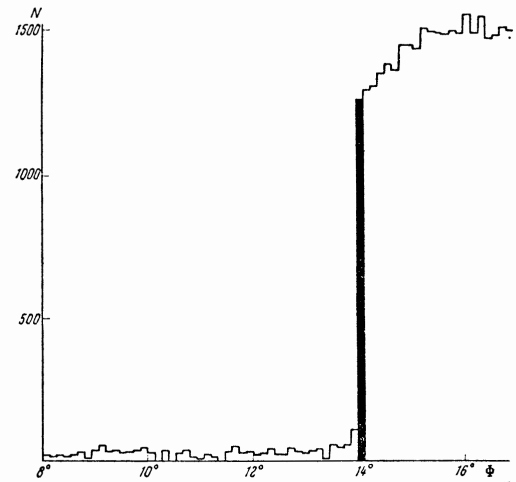

FIG. 2. Distribution of the divergence angle of π^0 decay γ rays.

marked division in the distribution of divergence angles for decay γ rays from single mesons and from two mesons, respectively. After subtracting the background, the prominent portion of the distribution was used to calculate the cross section by means of the equation

$$N=n\int_0^{4\pi}\int_0^{E_{max}}N(E)\,\varepsilon(E,\theta,\Phi)\frac{d\sigma}{d\Omega}dE\,d\Omega, \quad (6)$$

where n is the number of nuclei per cm^2 in the target, N is the registered number of decays, Ω represents the angular coordinates of the direction of decay γ rays, and N(E)dE is the number of photons having energies from E to E + dE in a bremsstrahlung beam having the maximum energy E_{max} (measured with a pair magnetic spectrometer). The function $\epsilon(E, \theta, \Phi)$ is the probability that the apparatus will register a π^0 meson with energy E emitted at the angle θ to the bremsstrahlung beam. We calculated $\epsilon(E, \theta, \Phi)$ averaged over the azimuthal angle; the angle θ was measured from 0° to 5° in steps of 20′; the energy varied from 900 to 1100 MeV in steps of 20 MeV. Our model was based on a point target, with π^0 emission at different angles θ (and at all azimuthal angles) and isotropic meson decay in the π^0 rest system. The fraction of γ-γ coincidences was determined for divergence angles from Φ_{min} to $\Phi_{min}+\delta$ at a given energy E. The calculations took into account the decay γ-ray losses in the target, in air along the path to the spark chambers, in the scintillators of counters C_1, and in the aluminum plate at the first gap of SC_1, as well as the loss of events due to fluctuations in the number of shower tracks. For the calculations the shower development in SC_2 was based on the distribution obtained in the

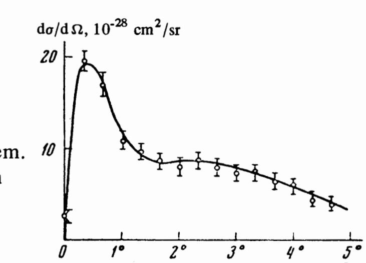

FIG. 3. Distribution of π^0 mesons in the laboratory system. The curve was calculated from Eq. (9).

preliminary experiments. The function $\epsilon(E, \theta, \Phi)$ was calculated by the Monte Carlo method with ±2% accuracy.

Figure 3 shows points calculated according to (6). The error bars denote the total errors, which include those already mentioned and also the ±1% error in determining the target thickness, the statistical errors, and the ±3% error that is introduced when subtracting the background.

EXPERIMENTAL RESULTS

The method proposed by Primakoff has been used[9,10] to determine the π^0 lifetime. Neglecting the recoil energy of the target nucleus, the cross section for π^0 photoproduction in the Coulomb field of a nucleus is given by

$$\frac{d\sigma_{\text{Coul}}}{d\Omega} = \frac{Z^2}{\tau_{\pi^0}} \frac{8\beta^3 E^4}{137\mu_{\pi^0}^3} \frac{|F_{em}(q)|^2}{q^4} \sin^2\theta, \tag{7}$$

where Z is the charge of the target nucleus; E, the incident photon energy, equals the total energy of the π^0 meson; μ_{π^0}, β, and θ are the mass, velocity and emission angle of the meson; $F_{em}(q)$ is the electromagnetic form factor of the nucleus; q is the momentum of the recoiling nucleus.

The differential cross section for coherent nuclear photoproduction of pions is given by

$$d\sigma_{\text{nuc}}/d\Omega = {}^1\!/_2 |\eta|^2 A^2 |F_N(q)|^2 \sin^2\theta, \tag{8}$$

where

$$\eta = (2\pi\rho_N)^{1/2}\left(L_0 + \frac{2Z - A}{A} N_0\right).$$

Here L_0 and N_0 are the amplitudes of π^0 photoproduction on nuclei; ρ_N is the distribution of nucleons in the nucleus; A is the nuclear mass number; $F_N(q)$ is the nuclear form factor; η is a complex quantity which is unknown, generally speaking.

Experimental mode	τ_{π^0}, 10^{-16} sec
$K^{+}_{\pi_2} \to \pi^+ + e^+e^-$	1.9 ± 0.5 [11]
»	$2.3 \pm^{1.1}_{1.0}$ [12]
»	$1.6 \pm^{0.6}_{0.5}$ [13]
»	1.0 ± 0.5 [14]
$\pi^- Z \to \pi^0 Z' \to e^+e^- Z'$	1.7 ± 0.5 [15]
»	1.05 ± 0.18 [16]
$\gamma Z \to \pi^0 Z \to 2\gamma Z$	0.73 ± 0.105 [4]
»	$0.60 \pm^{0.2}_{0.08}$ [5]
»	0.90 ± 0.068

Since the Pauli principle strongly forbids meson production on nuclei at small angles, the resultant cross section is

$$\frac{d\sigma}{d\Omega} = \sin^2\theta \left| \frac{a(\theta)}{\sqrt{\tau_{\pi^0}}} F_{em}(q) + e^{i\delta} F_N(q) \right|^2, \tag{9}$$

where δ is the phase of the complex amplitude $L_0 + [(2Z - A)/A]N_0$, and C is an unknown quantity that can be considered a constant in the small angle region. Thus τ_{π^0}, δ, and C are unknown parameters that must be determined experimentally.

The form factors that account for pion absorption in the nucleus, were calculated by Morpurgo's method.[9] The experimental data were analyzed in the 0°–3° angular interval, where photoproduction in the nuclear Coulomb field plays the main role and the cross section for the Primakoff effect depends only on τ_{π^0}, δ, and C. A least-squares analysis yielded the following values of the parameters:

$$\tau_{\pi^0} = (0.90 \pm 0.068)\cdot 10^{-16}\,\text{sec}, \quad C = 77 \pm 5\ \mu\text{b/sr}, \quad \delta = 82^\circ \pm 5^\circ.$$

The given errors correspond to one standard deviation. The accompanying table gives the π^0 lifetime measurements that have been published up to the present time.

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220