[1]V. N. Gribov, Yad. Fiz. 17, 603 (1973) [Sov. J. Nucl. Phys. 17, 313 (1973)].
[2]A. A. Migdal, A. M. Polyakov, and K. A. Ter-Martirosyan, Zh. Eksp. Teor. Fiz. 67, 84 (1974) [Sov. Phys. JETP 40, 43 (1975)]; H. D. I. Abarbanel and J. B. Bronzan, Phys. Rev. D9, 2397 (1974).
[3]P. D. B. Collins, F. D. Gault, and A. Martin, Phys. Lett. 47B, 171 (1973); Nucl. Phys. B80, 135 (1974); Nucl. Phys. B83, 241 (1974).
[4]V. Barger, Proc. 17th Intern. Conf. on High Energy Physics, London, 1974.
[5]H. Cheng and T. T. Wu, Phys. Rev. Lett. 24, 1456 (1970).
[6]G. Auberson, T. Kinoshits, and A. Martin, Phys. Rev. D3, 3185 (1971).
[7]V. Barger, F. Halzen, T. K. Gaisser, C. J. Noble, and G. V. Yodh, Phys. Rev. Lett. 33, 1051 (1974).
[8]O. V. Kancheli, Pis'ma Zh. Eksp. Teor. Fiz. 18, 469 (1973) [JETP Lett. 18, 277 (1973)].
[9]Z. Koba, H. B. Nielsen, and P. Olesen, Nucl. Phys. B40, 317 (1972).
[10]V. A. Abramovski, V. N. Gribov, and O. V. Kancheli, Proc. 16th Intern. Conf. on High Energy Physics, Chicago-Batavia, 1972.
[11]K. A. Ter-Martirosyan, Phys. Lett. 44B, 377 (1973).
[12]M. S. Dubovikov and K. A. Ter-Martirosyan, Intern. Conf. on Fundamental Interactions of Elementary Particles, Coral Gables, 1976.
[13]Yu. M. Kazarinov, B. Z. Kopeliovich, L. I. Lapidus, and I. K. Potashnikova, JINR E2-9218, Dubna, 1975.
[14]J. L. Cardy, Nucl. Phys. B75, 413 (1974).

Translated by J. G. Adashko

Investigation of the $\pi^+ \to e^+ + \nu_e + e^+ + e^-$ decay

S. M. Korenchenko, B. F. Kostin, G. V. Mitsel'makher, K. G. Nekrasov, and V. S. Smirnov

Joint Institute for Nuclear Research
(Submitted March 4, 1976)
Zh. Eksp. Teor. Fiz. 71, 69–77 (July 1976)

An experiment has been carried out on the $\pi^+ \to e^+ + \nu_e + e^+ + e^-$ decay. Five events were found and could essentially be interpreted as $\pi^+ \to e^+ + \nu_e + \gamma$ decays although they should also contain $\pi^+ \to e^+ + \nu_e + e^+ + e^-$ events with a probability of over 1/2. The ratio γ of the axial and vector formfactors in the $\pi^+ \to e^+ + \nu_e + \gamma$ decay is reported together with the estimated upper limits for the formfactors ξ in the $\pi^+ \to e^+ + \nu_e + e^+ + e^-$ decay and the electromagnetic radius of the pion. An upper limit has been established for the probabiity of the latter decay mode: $W_{\pi \to e\nu ee}/W_{\pi \to \mu\nu} < 4.8 \times 10^{-9}$ with a confidence level of 90% on the assumption that the decay matrix element is a constant.

PACS numbers: 13.20.Cz, 14.40.Dt

1. INTRODUCTION

No one has so far observed the

$$\pi^+ \to e^+ + \nu_e + e^+ + e^- \quad (1)$$

decay. In a previous paper,[1] we reported that the upper limit for the relative decay probability was

$$R = W(\pi^+ \to e^+ + \nu_e + e^+ + e^-)/W(\pi^+ \to \mu^+ + \nu_\mu) < 3{,}4 \cdot 10^{-8} \quad (2)$$

with a 90% confidence level. In the present paper, we report the results of a new experiment performed at the Laboratory for Nuclear Problems of the Joint Institute for Nuclear Research in which searches for the decay mode given by (1) were carried out. Preliminary results of this experiment were reported in[2].

The $\pi \to e\nu ee$ decay mode was first considered by Okun', Pontecorvo, and Rubbia[3] in connection with the possible existence of an anomalous four-lepton interaction. However, estimates based on experiments using colliding electron-positron beams[4] lead to an exceedingly low decay probability for this diagram ($R < 2 \times 10^{-15}$).

The $\pi \to e\nu ee$ decay may proceed as a result of a six-fermion interaction, the possible existence of which was first suggested by Glashow.[5] The corresponding decay diagram is shown in Fig. 1. The probability of decay due to the six-fermion interaction has been calculated by Vanzha, Isaev, and Lapidus.[6] The corresponding interaction constant is conveniently written in the form

$$G_6 = \frac{G}{\sqrt{2}} \frac{1}{\lambda^3}, \quad (3)$$

where G is the usual four-fermion interaction constant. The parameter λ has the dimensions of mass and is usually employed to characterize the constants G_6. It was found in[6] that

$$R = 1.25 \cdot 10^{-4} (m_\mu/\lambda)^6, \quad (4)$$

where m_μ is the muon mass.

The upper limit for the probability of the decay mode

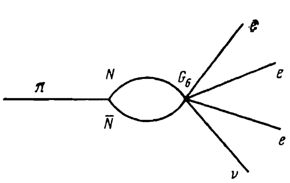

FIG. 1. Diagram representing the $\pi \to e\nu ee$ decay due to the six-fermion interaction.

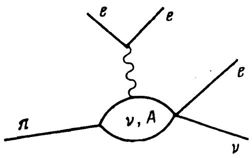

FIG. 2. Diagram representing the structure dependence (V, A) part of the $\pi\rightarrow e\nu ee$ decay.

(1), reported in[1], has enabled us to obtain a better estimate for λ ($\lambda > 410$ MeV) than the value obtained in[7] on the basis of neutrino experiments ($\lambda > 100$ MeV).

The $\pi\rightarrow e\nu ee$ decay may proceed, due to known weak-interaction and electromagnetic forces, as an internal conversion process in the radiative decay of the pion. The most interesting feature is that part of the decay in which the emission is determined by the internal structure of the pion, as shown in Fig. 2.

The structure-dependent part of the $\pi\rightarrow e\nu ee$ decay was first considered by Flagg[8] from the standpoint of a possible violation of T-invariance in this decay. It was found that the associated effects were very small, and the necessary measurements had to be carried out with relative probabilities of $10^{-13}-10^{-14}$.

Studies of the structure-dependent pion-decay modes (and the analogous decays of the kaon) due to the simultaneous manifestation of weak-interaction and electromagnetic forces are interesting because they yield more extensive information about the structure of hadrons than can be obtained by studying purely weak-interaction or electromagnetic processes alone. These decays are described by the matrix element evaluated between vacuum and the $\pi(K)$ meson state involving two hadron currents, i.e., weak and electromagnetic. Thus, these semilepton decays provide information on the weak and electromagnetic structure of pseudoscalar mesons in the purest form. The leptons, which do not exhibit strong interactions, then act as "perfect probes" of the hadron structure.

The amplitude for the $\pi\rightarrow e\nu ee$ decay is discussed most extensively by Bardin *et al.*[9] According to these workers, in addition to the vector and axial vector formfactors $a(0)$ and $b(0)$, which also determine the structure-dependent part of the radiative decay of the pion ($\pi\rightarrow e\nu\gamma$), the structure-dependent part of the $\pi\rightarrow e\nu ee$ decay contains a contribution of a further axial formfactor ξ which is connected with the emission of longitudinally polarized virtual photons. Vaks and Ioffe[10] have shown that the hypothesis of isotriplet character of the vector current can be used to relate $a(0)$ to the amplitude for the $\pi^0\rightarrow 2\gamma$ decay, i.e., in the final analysis, it can be used to determine this quantity from the lifetime τ_{π^0} of the neutral pion.

The probabilities of the $\pi\rightarrow e\nu\gamma$ and $\pi\rightarrow e\nu ee$ modes can be conveniently expressed in terms of the ratio:

$$\gamma=b(0)/a(0). \tag{5}$$

The quantity γ has been determined in experiments concerned with the $\pi\rightarrow e\nu\gamma$ decay.[11,12] Two possible values were obtained: $\gamma=0.15-0.4$ or $\gamma=-2$. It has not been possible to choose unambiguously between these two possibilities.

If we use the hypothesis of partial conservation of axial current, the current algebra, and the assumption of a weak dependence of formfactors on the transferred momentum, it can be shown that[9,13]

$$\xi=-s\frac{1}{3\sqrt{2}}\left|\frac{f_\pi}{a_0}\right|\langle r_\pi^2\rangle, \tag{6}$$

where $s=\operatorname{sign}(f_\pi a_0)$, f_π is the amplitude for the $\pi\rightarrow e\nu$ decay, a_0 is the amplitude for the $\pi^0\rightarrow 2\gamma$ decay, and r_π is the electromagnetic radius of the pion. The ratio R of the probability $W_{\pi\rightarrow e\nu ee}$ of the $\pi\rightarrow e\nu ee$ decay of the total probability $W_{\pi\rightarrow\mu\nu}$ of the decay of the pion is given by

$$\begin{aligned}R=&IB+(SD+\gamma\,SD_\gamma+\gamma^2\,SD_{\gamma^2}+\gamma\xi\,SD_{\gamma\xi}+\xi\,SD_\xi\\&+\xi^2\,SD_{\xi^2})\tau^2+(IB\,SD+\gamma\,IB\,SD_\gamma+\xi\,IB\,SD_\xi)s\tau.\end{aligned} \tag{7}$$

In this expression, IB is the contribution of internal bremsstrahlung, SD_ξ represents, for example, the total contribution of interference between the vector part of the amplitude and its part proportional to ξ, and so on; $\tau=0.89\times10^{-16}/\tau_{\pi^0}$.

Calculations of the quantities IB, SD, and so on in different kinematic regions show[9] that, for positron energies in excess of 15 MeV, the relative contribution of the term IB is substantially reduced. It also turns out that the influence of the formfactor ξ is important only in the region where there are practically no correlated electron-positron pairs (the value of the invariant masses of e^+e^- pairs is 15–20 MeV). The last feature can be used to separate the contributions of the parameters γ and ξ.

Thus, detailed studies of $\pi\rightarrow e\nu ee$ decays can be used, at least in principle, a) to determine γ, b) to determine the formfactor ξ, and c) knowing ξ, or by assuming a value for the electromagnetic radius of the pion taken from other experiments, to check the validity of hypotheses upon which the derivation of (6) is based (the hypothesis of partial conservation of axial current and the relationships of current algebra) or, conversely, assuming (6) to determine the electromagnetic radius of the pion and the relative sign of the amplitude for the $\pi\rightarrow e\nu$ and $\pi^0\rightarrow 2\gamma$ decays.

Unfortunately, in the kinematic region in which we are interested, the probability of the process is very low and lies at the level of $10^{-9}-10^{-10}$ of the probability of the usual decay mode.

We report below the results of experiments in which an attempt was made to detect the decay mode given by (1). Detailed studies of this process can, of course, be carried out only with the strong beams produced by meson factories.

2. PRINCIPLE OF THE EXPERIMENT

Searches for the decay mode (1) were carried out simultaneously with searches for $\mu^+\rightarrow e^+ + e^+ + e^-$ decays.[14] We used a magnetic spark spectrometer[15] consisting of an 18-gap cylindric spark chamber located

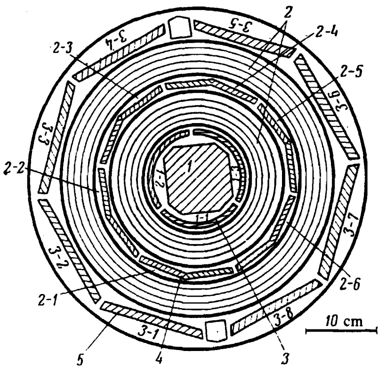

FIG. 3. Section through the spectrometer in the plane perpendicular to the direction of the pion beam: 1—target, 2—spark chamber gap, 3—three scintillators in the first row, 4—six scintillators in the second row, 5—eight scintillators in the third row.

in a magnetic field and controlled by a hodoscopic system consisting of 19 scintillation counters located both inside and outside the chamber (Fig. 3). The chamber diameter was 39 cm and its height 28 cm. Pulses from the scintillation counters were displayed on a five-beam oscillograph.

The spectrometer was placed in the 80-MeV positive-pion beam of the synchrocyclotron at the Laboratory for Nuclear Problems of the Joint Institute for Nuclear Research. The pions came to rest in a target consisting of a plastic phosphor of $22\times100\times180$ mm. The target was placed inside the chamber, at an angle to the beam, so that its projection onto the plane perpendicular to the beam had an area of 100×100 mm and the amount of material in the path of the beam was 3.6 g/cm^2. Fast-logic electronics was used to generate a gating pulse whenever a coincidence was produced within the resolving time of the electronics (~10 nsec) between the eight pulses originating in the target and in any two scintillation counters in the first row, two counters in the second row, and three counters in the third row (Fig. 3). A further requirement was that this coincidence had to lie within the limits of a time "gate," 70 nsec long and beginning 5 nsec after the stoppage of the pion.

A total of 4.1×10^{10} pions came to rest during the 620 hours of exposure, and 588×10^3 pairs of photographs of the chamber and of the oscillograph screen, in which events of the form (1) could be present, were recorded. About 64% of these exposures were obtained in a magnetic field of 0.45 T. Analysis of the data obtained as a result of this exposure showed that the background level was low. To increase the efficiency of detection of the process (1), subsequent exposures were therefore carried out in a magnetic field of 0.3 T.

3. SELECTION AND ANALYSIS OF EVENTS

The preliminary selection of events was based on the following criteria:

1) the presence of two positron tracks and one electron track;

2) all tracks reached the third row of scintillation counters and passed through different counters in this row;

3) at least five sparks were present on each track;

4) the oscillogram of the event contained pulses from the scintillation counters traversed by the particles.

Photographs obtained in the field of 0.45 T were scanned once and a proportion of the photographs twice. The entire material obtained in the field of 0.3 T was scanned twice, and some of the photographs three times As a result, 794 photographs were selected for further analysis. The coordinates of the tracks corresponding to these events were examined under microscopes with automatic data readout.[16] The resulting data were then analyzed on a computer. The χ^2 test was used to determine whether all three tracks could emerge from a single point in the target. Events with a value of χ^2, for which the probability was less than 5%, were rejected. These procedures finally resulted in a residual 68 possible events. The χ^2 test was then again used to determine whether the observed decay kinematics was consistent with the hypothesis that this was a decay of the form (1). Events with a value of χ^2 corresponding to a probability of less than 5% were assumed to belong to the background. After this procedure, there were finally 12 events that could be regarded as possible candidates for the decay (1).

4. BACKGROUND PROCESSES

Apart from the intensity of the beams and the efficiency of the equipment, the determining factor in searches for rare decay modes is the presence of a background and the ability to separate it from the required process.

In searches for the decay mode (1), the possible sources of background are the following processes:

I) charge transfer from the positive pion to the target nuclei, resulting in a neutral pion which subsequently decays into the three charged particles that are recorded;

II) the $\pi^+\to e^+ + \nu_e + \gamma$ decay with subsequent conversion of the gamma ray in the target into an electron-positron pair;

III) the $\pi^+\to e^+ + \nu_e + \bar{\nu}_\mu + \gamma$ decay with subsequent conversion of the gamma ray in the target;

IV) the $\mu^+\to e^+ + \nu_e + \bar{\nu}_\mu + e^+ + e^-$ decay;

V) random coincidences between two positrons from muon decays in which one of the positrons is scattered by an electron in the target transferring to it a sufficient amount of energy (>10–15 MeV);

VI) random coincidences between a positron from a muon decay and the transit of a charged particle from a region outside the chamber through the entire chamber and the target; a particle of this kind will stimulate a positron and an electron.

Process I has, in general, very low probability and is totally eliminated by the requirement that the recorded decay does not coincide with the time of stoppage of the pion.

To suppress the contribution of process VI, the selected events were χ^2 tested for through transits.

To obtain a clearer idea about the background conditions, all the events obtained in the general exposure (both $\mu^+ \to e^+ + e^+ + e^-$ and $\pi^+ \to e^+ + \nu_e + e^+ + e^-$) were analyzed by the same program independently of which mode was being considered. This enabled us to obtain a more accurate correction for the background in the case of the decay mode (1). In particular, it was found that events corresponding to a through transit were due to positrons from an outer part of the chamber in at least 98% of all cases. This was established from the difference between particle energy on either side of the target. Through-transit events were therefore rejected if they corresponded to a positron, or if the sign of the particle could not be unambiguously established.

Of the 12 remaining candidates, 7 events turned out to be due to the background associated with through transits.

Processes II–V are characterized by the fact that they should contain an electron-positron pair with a small invariant mass. To estimate the possible contribution of such processes, we determined the invariant mass for both possible combinations of two positrons and an electron for all the recorded events.

We found that the remaining five events had an e^+e^- pair with invariant mass less than 20 MeV. This did not, however, mean that they all belonged to the background. The fact that the three-track events found in searches for the $\mu \to eee$ decay were also analyzed by the program designed to isolate events with $\pi \to e\nu ee$ kinematics enabled us to estimate the contribution of processes III–V connected with muon decays. Among events connected with muon decays, we found 21 events with kinematics simulating $\pi \to e\nu ee$. If the III–V processes were to imitate the $\pi \to e\nu ee$ decay, they would have to satisfy an additional condition, namely, they would have to lie within the time gate. Moreover, since only one pulse should be present in the gate, the simulation can be produced either by an event in which a pulse from the $\mu \to \mu\nu$ decay is superimposed on the pion stopping pulse, and cannot be seen, or when there is a random coincidence within the gate between the decay of the pion and the processes III–V.

The time t_0 during which the $\pi \to \mu$ pulse may not be identified will, of course, depend on the amplitude of the stoppage and decay pulses. Estimates based on available oscillograms yield ~8–12 nsec. The mean stoppage rate and, consequently, the number of gates per second was $B = 2\times 10^4$ sec^{-1} in our exposure. Hence, the coefficient K representing the suppression of the background due to processes III–V is not more than

$$K = \frac{t_0}{\tau_\pi}\left(\frac{t}{\tau_\mu} + tB\delta\right) \approx 1.5\cdot 10^{-2}, \qquad (8)$$

where τ_π is the pion lifetime, t is the length of the gate, and $\delta \approx 3$ is the beam duty factor.

According to (8), the background due to processes III–V can be estimated as

$$n_{3-5} \sim 0.5 \text{ events}. \qquad (9)$$

Thus, practically all the five remaining candidates may be looked upon as connected with $\pi \to e\nu ee$ and $\pi \to e\nu\gamma$ events.

5. UPPER LIMIT FOR THE PROBABILITY OF THE $\pi^+ \to e^+ + \nu_e + e^+ + e^-$ DECAY (EVENTS WITHOUT CORRELATED PAIRS)

We have already pointed out that all the five remaining candidates for (1) have the e^+e^- pair that is characteristic for decays including electromagnetic processes. Hence, it may be concluded that none of these events can be interpreted as the decay (1) due to interactions that do not result in correlated e^+e^- pairs (six-fermion, anomalous four-lepton).[1]

The efficiency of detection of the decay mode (1) was calculated by the Monte Carlo method on the assumption that the matrix element for the decay was a constant. We took into account the geometry of the spectrometer, the ionization losses in the target, the gating logic, and the magnetic field.

The efficiency obtained by simulation was then corrected by introducing the coefficient

$$e = e_1 e_2 e_3 e_4 e_5 e_6, \qquad (10)$$

where $e_1 = 0.84$ is the correction for the efficiency of the scintillation counters, $e_2 = 0.95$–0.99 is the correction for losses connected with the deadtime of the photographic cameras, $e_3 = 0.76$ represents the introduction of the time gate, $e_4 = 0.9$ takes into account the use of the confidence levels based on χ^2, $e_5 = 0.71$ is a correction connected with the rejection of through transits and e^+e^- pairs, and e_6 represents the scanning efficiency and the shower efficiency of the chamber.

The scanning efficiency was usually determined from the results of two or more scans of the material available. When the efficiency of both scans is the same and independent of the particular type of the event, the resultant efficiency can be simply determined. In our case, it turned out that the scanning efficiency depended on the number of sparks per track, i.e., on the shower efficiency of the chamber. In order to take this into account, the selected events were classified in accordance with the number of sparks on a track with a minimum number of sparks (minimum track). It was found that only those events for which the minimum track contained not less than 8 sparks could be selected with an efficiency approaching 100%. According to the selection criteria, however, those events were selected for which there were five or more sparks per track. The efficiency of selecting events under these conditions was estimated with the aid of a simulation. First, the existing experimental events were used to establish whether or not all the gaps in the chamber had roughly the same efficiency and whether the distribution of sparks in the gaps could be described by the binomial law. The binomial distribution was then used in a simulation procedure to determine the distribution of sparks in three-track events for different values of the efficiency of a single gap ε_1. Tracks were then selected from the simulated events for which the minimum track had not less than eight sparks. This was used to determine the apparent efficiency ε_b of an individual gap. It is clear that $\varepsilon_1 < \varepsilon_b$. The dependence of ε_1 on ε_b obtained in this way, taken together with the experimental data obtained with an efficiency of about 100% (events with number of sparks on a minimum track not less than 8), enabled us to determine with good accuracy the true value of ε_1. The same data were also used to determine the total number of three-track events (with any number of sparks per track) and hence the selection efficiency e_6. The value of e_6 in a field of 0.45 T was found to be 0.6, whereas the value for a field of 0.3 T was 0.76. The difference between these values of e_6 is due to the different number of scans of the available material.

The coefficient e was taken to be 0.23 in the field of 0.45 T and 0.31 in the field of 0.3 T. The total detection efficiency in the field of 0.45 T was 0.008 ± 0.002 and the efficiency in the field of 0.3 T was 0.018 ± 0.004. The number of pion decays in the field of 0.45 T was 2.64×10^{10} and the corresponding figure in the field of 0.3 T was 1.46×10^{10}.

Using the Poisson distribution, we obtained the following upper limit for the probability of the decay mode (1) as a fraction of the main pion decay mode:

$$W_{\pi\to e\nu ee}/W_{\pi\to\mu\nu} \leqslant 4.8 \cdot 10^{-9} \tag{11}$$

with a 90% confidence level.

This upper limit for the decay mode (1) can be used to obtain the following result for the six-fermion interaction constant:

$$\lambda > 575 \text{ MeV}. \tag{12}$$

Gershteĭn and Folomeshkin[17] have reported an estimate of λ based on the experimental limits on the total cross sections for the interaction of high-energy cosmic neutrinos. They assumed that the total cross section increased in the same way as for point particles. In this case, the result was

$$\lambda > 1.25 \text{ BeV}. \tag{13}$$

It follows that the estimate given by (10) is inferior only to the estimates based on cosmic neutrino data.

6. THE $\pi^+ + e^+ + \nu_e + e^+ + e^-$ DECAY (WEAK AND ELECTROMAGNETIC INTERACTIONS)

Estimates have shown that the expected mean background is 0.5 events. With a probability of 90%, therefore, four or five of our events can be identified as $\pi \to evee$ or $\pi \to e\nu\gamma$, followed by the conversion of the gamma ray.

To determine the contributions of these decays to our events, we used the Monte Carlo method both for (1) and for $\pi^+ \to e^+\nu_e\gamma$ to calculate the differential detection probabilities as functions of the cosine of the angle between the single positron and the direction of emission of the e^+e^- pair. We calculated separately the γ-independent contribution and the contributions that were functions of γ and γ^2. We took into account the geometry of the installation, the gating logic, and all the other experimental conditions affecting detection efficiency. We found that the ratio of the contributions of processes such as (1) and $\pi^+ \to e^+ + \nu_e + \gamma$ was $\sim \frac{1}{6}$ and was not very dependent on γ. This means that the events which we have found are mainly $\pi^+ \to e^+ + \nu_e + \gamma$ decays.

Calculations have also shown that both decay modes are detected mainly in the region that is sensitive to the structure-dependent part. This region is characterized by the fact that the angle between the single positron and the pair exceeds 90°. All the five residual cases were found to belong to precisely this region. Since the probabilities of both decays are functions of γ, these calculations and the above experimental data can be used to estimate the magnitude of γ.

Taking into account the expected background (~0.5 events), assuming $\tau_{\pi^0} = 0.84 \times 10^{-16}$ sec, and using the Poisson distribution, we find, with a 90% confidence level, that

$$\gamma = -2.15^{+1.65}_{-1.0} \quad \text{or} \quad \gamma = 1.0^{+1.05}_{-1.5}. \tag{14}$$

These values are in agreement with the results of more precise measurements made on $\pi^+ \to e^+ + \nu_e + \gamma$ decays.[11,12] It is important to note that the $\pi^+ \to e^+ + \nu_e + \gamma$ decay mode was recorded in our experiments in a broader range of angles and energies than in[11,12].

To estimate the magnitude of the formfactor ξ, its contribution to the process (1) was calculated by the Monte Carlo method with allowance for the experimental conditions (gate logic, magnetic field, etc.). According to these calculations, the dependence of the number of events without correlated pairs on γ and ξ ($\tau_{\pi^0} = 0.84 \times 10^{-16}$ sec) is

$$N = (1470 + 2.8\gamma - 5.1\xi - 29.8\gamma\xi + 22.3\gamma^2 + 23.3\xi^2) \cdot 10^{-3}. \tag{15}$$

Since the decay mode (1) was not found, we have, using (15),

$$|\xi| < 7. \tag{16}$$

This restriction on ξ can be used with (6) to establish, with a 90% confidence level, that

$$r_\pi < 1.1 \text{ F}. \tag{17}$$

The result given by (16) is in agreement with experimental values of the electromagnetic radius of the pion.[18] This means that the dependence given by (6) is not inconsistent with known experimental data.

Our experiment did not demonstrate the existence of the decay mode (1). Nevertheless, if we regard as valid the assumption of the existence of this decay due to weak and electromagnetic interactions, then, with a probability of 55%, the recorded events should include decay modes of the form given by (1).

Our results also show that, for a reliable detection of the decay mode (1), one should use not only higher-intensity beams but also thinner targets or methods of detecting the decays in flight so as to reduce the background due to $\pi^+ \to e^+ + \nu_e + \gamma$ decays.

The authors are indebted to V. P. Dzhelepov, L. I. Lapidus, and B. M. Pontecorvo for help and interest in this research, D. Yu. Bardin and S. M. Bilen'kiĭ for valuable discussions, V. A. Enchevich for scanning the enormous number of photographs, N. A. Kuchinskiĭ, I. Yu. Levenberg, S. A. Panchuk, and N. L. Savel'ev for assistance in the processing of the data, and G. K. Kocheshkov, E. N. Ul'yanov, and I. M. Shirokov for participation in the preparation of the equipment and in carrying out the experiments.

[1)]The part of the structure-dependent decay that is sensitive to the formfactor ξ does not produce correlated pairs either (see Sec. 6).

[1]S. M. Korenchenko, B. F. Kostin, G. V. Mitsel'makher, K. G. Nekrasov, and V. S. Smirnov, Yad. Fiz. 13, 339 (1971) [Sov. J. Nucl. Phys. 13, 189 (1971)].
[2]S. M. Korenchenko, B. F. Kostin, G. V. Mitsel'makher, K. G. Nekrasov, and V. S. Smirnov, JINR, R1-6760, Dubna, 1972; JINR, R1-9231, Dubna, 1975.
[3]L. Okun', B. Pontecorvo, and K. Rubbia, Yad. Fiz. 4, 1202 (1966) [Sov. J. Nucl. Phys. 4, 864 (1967)].
[4]B. L. Beron *et al.*, Phys. Rev. Lett. 33, 663 (1974).
[5]S. L. Glashow, Nucl. Phys. 22, 579 (1961).
[6]A. Vanzha, A. Isaev, and L. Lapidus, Yad. Fiz. 12, 595 (1970) [Sov. J. Nucl. Phys. 12, 325 (1970)].
[7]T. Ericson and S. L. Glashow, Phys. Rev. B 133, 130 (1964).
[8]W. Flagg, Phys. Rev. 178, 2387 (1969).
[9]D. Yu. Bardin, S. M. Bilen'kiĭ, G. V. Mitsel'makher, and N. M. Shumeĭko, Yad. Fiz. 14, 427 (1971) [Sov. J. Nucl. Phys. 14, 239 (1971)].
[10]V. G. Vaks and B. L. Ioffe, Nuovo Cimento 10, 342 (1958).
[11]P. Depommier, I. Heintze, C. Rubbia, and V. Soergel, Phys. Lett. 7, 285 (1963).
[12]A. Stetz, I. Carrol, *et al.*, Phys. Rev. Lett. 33, 1455 (1974).
[13]T. Das, V. S. Mathur, and S. Okubo, Phys. Rev. Lett. 19, 470 (1967).
[14]S. M. Korenchenko, B. F. Kostin, G. V. Mitsel'makher, K. G. Nekrasov, and V. S. Smirnov, JINR, R1-8875, Dubna, 1975.
[15]S. M. Korenchenko, A. G. Morozov, K. G. Nekrasov, and Yu. V. Rodnov, JINR, R13-5170, Dubna, 1970.
[16]V. A. Almazov, I. G. Golutvin, V. D. Inkin, Yu. A. Karzhavin, V. D. Neustroev, and V. D. Stepanov, JINR, 1352, Dubna, 1963.
[17]S. S. Gershteĭn and V. N. Folomeshkin, Yad. Fiz. 15, 534 (1972) [Sov. J. Nucl. Phys. 15, 299 (1972)].
[18]G. T. Adylov *et al.*, Phys. Lett. B 51, 356 (1974).

Translated by S. Chomet

Ultrahigh resolution spectroscopy based on wave competition in a ring laser

E. M. Belenov, M. V. Danileĭko, V. R. Kozubovskiĭ, A. P. Nedavniĭ, and M. T. Shpak

Physics Institute, Ukrainian Academy of Sciences
(Submitted September 8, 1975)
Zh. Eksp. Teor. Fiz. 71, 78–87 (July 1976)

A novel method in which "Lamb dips" are not employed is developed for nonlinear laser spectroscopy. Its feasibility is based physically on the competition between spectral and spatial bleaching effects of the gas lines and of phase interaction of ring-laser traveling waves. The hyperfine structure of the absorption line of excited neon for the $4p\,{}^1[3/2]_2 \to 5s\,{}^1[1/2]_1$ transition, which is due to the presence of isotopes in the absorbing medium, is studied by this method. The superiority of a ring laser over a linear one is confirmed: its sensitivity is much higher and the registration is considerably simpler (such studies have not been performed at all with linear lasers). Precision measurements of Zeeman splitting of the methane absorption line belonging to the $F_1^{(2)}$ component of the ν_3-group $P(7)$ branch are made with a ring laser with a resolution 2×10^{-6} cm^{-1}. It is demonstrated that the sensitivity and accuracy of a nonlinear ring-laser spectroscope when used to investigate the hyperfine structure of weakly absorbing gases can be enhanced by operating in self-oscillation generation regimes.

PACS numbers: 07.45.+r, 42.60.Qm

INTRODUCTION

The presently employed methods of nonlinear laser spectroscopy (NLS) without Doppler broadening (see, e.g., [1]) are based on effects of spectral saturation of the gas in the field of a strong light wave, [2–4] which leads to the onset of narrow nonlinear resonances against the background of a broad Doppler gain contour or absorption contour of width equal to the homogeneous line width (the so-called "Lamb dips"[4]). The sensitivity and accuracy of these methods are determined by the magnitude and width of the Lamb dips, while the resolution is determined by the homogeneous line width of the amplifying or absorbing gas. In the optical band, the ratio of the Doppler width $\Delta\omega_D = ku$ to the homogeneous width Γ is $ku/\Gamma \sim 10^2 - 10^4$, i.e., the resolving power of NLS exceeds the resolving power of linear spectroscopy by several orders of magnitude.