СООБЩЕНИЯ
ОБЪЕДИНЕННОГО
ИНСТИТУТА
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ
Дубна

E1 - 4786

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ЛАБОРАТОРИЯ ВЫСОКИХ ЭНЕРГИЙ

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(Proposal of the experiment)

1. Introduction

Measurements of the electromagnetic structure of the π-meson, one of the main particle in the hadron family, is of great interest in high energy physics. The hypothesis of vector dominance in the electromagnetic interactions of hadrons together with experiments on the determination of coupling constant V_γ permits to conclude about the π-meson form factor behaviour and predicts the electromagnetic radius for the π-meson ($\langle r^2 \rangle^{1/2} = 0.63$ fermi).

In recent years, some experiments on the π-meson form factor measurement in the reaction

$$\pi^{\pm} + e^{-} \to \pi^{\pm} + e^{-}$$

have been carried out using bubble chambers, with primary π-mesons momenta equal to 1.12, 4.0 and 16 GeV/c /1,2,3/. The estimation of the π-meson electromagnetic radius $\langle r^2 \rangle^{1/2} \leq 4.5$ has been obtained at 16 GeV/c in the last of these papers /3/.

The possibility of obtaining of π^--meson beams with momenta > 40 GeV/c permits to perform an experiment on more detailed measurements of the π-meson form factor in the reaction

$$\pi^{-} + e^{-} \to \pi^{-} + e^{-} ,$$

since at these energies the De Broglie wavelength of the electron is comparable to the Compton wavelength of the π-meson.

This proposal of experiment on beams of the accelerator of the Institute of High Energy Physics was developed during 1967-68 at the Laboratory of High Energies[x].

The performance of this experiment at a momentum of 50 GeV/c permits to measure the electromagnetic structure of the π -meson 0.7 f with an accuracy of 0.1f .

2. $\pi^- - e^-$ - Scattering

The scattering differential cross section of the point π -meson on the electron is expressed by

$$d\sigma_B/dq = K(q^{-3} - q^{-1} q_{max}^{-2}) \frac{mb}{MeV/c},$$

where $K = 520.98$ mb $(MeV/c)^2$, $q = \sqrt{-t}$ - the four-momentum transfer (MeV/c) to the electron, q_{max} - the maximum four-momentum transfer. Taking into account the π -meson form factor $F(q^2)$, the cross section of the process is determined by the formula:

$$d\sigma_F/dq = d\sigma_B/dq \; F^2(q^2).$$

For $h/q > r_\pi$, the series development of $F(q^2)$ can be used:

$$F(q^2) = 1 - q^2 r_\pi^2/6 + \dots .$$

The kinematic angle-momentum dependences of the secondary π -meson and electron for a 50 GeV/c momentum of the primary π -meson are presented in Fig.1. As is seen from Figures, there is a transfer interval q , for which it is impossible to find an unambiguous separation of events with a general counter for π and e (due to the finite accuracy of the measured angle). At 50 GeV/c this interval corresponds to q = 148 - 168 MeV/c and contains about

[x] This design is a further development of the proposal on the investigation of the electromagnetic structure of the π -meson, made by I.A. Golutvin, Yu.V. Zanevsky, V.G. Grishin, E.N. Tsyganov and V. Ryabtsev in March, 1967.

50 % measurable events with large momentum transfers. In order to avoid losses when detecting useful events, separate counters are used in the experimental device to record π^- and e^-.

Making of calibration measurements at small momentum transfers is a matter of some difficulty. In this case there are two possibilities: either changing the location of the π-meson and electron counters, but involving longer time at the accelerator, or constructing two-shower electron counters for calibration and main simultaneous measurements.

3. Experimental Layout

The analysis of background events and spurious triggerings showed the following: in order to set up the experimental device it is necessary to have a suppression of inelastic events as complete as possible by means of the greater number of anticoincidence counters. The experimental layout is presented in Fig.2.

The experimental set-up should operate as follows. A beam of primary π-mesons with a momentum of 50 GeV/c, incident on the hydrogen target T_H, is detected by the monitor scintillation counters S_1, S_2, S_3. In order to detect the π-meson and electron scattered, the scintillation counters S_4, S_5, S_6 are used. A spectrometer with the spark chambers SC5-8 and SC9-12 and the magnet M are used to analyse the momenta of scattered particles.

The spark chambers SC1-4 are applied to determine the coordinates and incoming angle of primary π-mesons into the hydrogen target. For the suppression of the inelastic interaction the hydrogen target is surrounded by the anticoincidence counters $A_1 - A_6$. A_6, located in the direction of the scattered π^- and e, discriminates against slow charged particles. The anticoincidence counter A_7 discriminates against fast positive particles.

The shower counter S_7, placed behind the electron counter S_6, discriminates against the arrival of the π^--meson at S_6. Between the π^--meson counter and the anticoincidence counter A_8

there is an absorber of μ^- -mesons. The spark chambers are triggered when all the coincidence counters operate, and signals from the anticoincidence counters are absent. Since the spark chambers are on-line with a computer, the device operation can be controlled.

4. Main Parameters of the Experimental Device and the Modelling of the Process of $\pi^- - e^-$-Scattering

1. In order to reduce the electron counter loading by the beam of primary π -mesons, it is necessary to have a beam size 3x3 cm^2, angular divergence of ≈ 1.5 mrad and $\Delta p/p \approx 1\%$. At present, there are some π^- -meson beams of such parameters with an intensity of $5 \cdot 10^4 \pi^-$ /cycle at 50 GeV/c ($3 \cdot 10^{11}$ protons/cycle in the accelerator chamber), at the Serpukhov accelerator.

2. Since the hydrogen target is almost completely surrounded by the anticoincidence counters, this permits to discriminate against inelastic events more than one order.

3. π -mesons will be negligibly suppressed (2 times) in the shower counter S_7 (a total absorption Cerenkov counter having a 18 x 20 x 30 cm^3 radiator) due to a large interval of detected momenta (25-37 GeV) at a 50 GeV/c momentum of primary π -mesons. However, with subsequence analysis of events, after the momentum of the detected particle has been determined by means of the spark chambers, π -mesons are suppressed no less than 30-50 times.

4. Using the anticoincidence counter A_8 , it is not difficult to suppress μ^- -mesons of one order. That permits to reduce their number to a reasonable value $\lesssim 1\%$.

5. Assume that the coordinate accuracy of the spark chambers is 0.4 mm. The spark chambers in each block are placed at a distance of 5 metres. In this case it is possible to measure the particle trajectory angles with an accuracy of 0.2 mrad. At 50 GeV/c, when the magnet SP-12 is used in the spectrometer, the mean deflection angles of π^- -mesons and electrons are equal to 90 mrad and 45 mrad, respectively. Thus, the measurement accuracies of the π^-

and e^- momenta are 0.2% and 0.5%. Nevertheless, the measurement error of the electron momentum determined by its radiative losses in the hydrogen target (50 cm length) is $\approx$ 2%. The accuracy of the π^- and e^- emergence angles is determined by multiple scattering in H_2 and is equal to $\approx$ 0.2 mrad.

To estimate measurement possibilities of the electromagnetic structure of the π-meson and the contribution of different experimental errors to the final physical result, the $\pi - e$ scattering modelling was performed on a computer.

The calculations made, using the scattering kinematics, permitted to choose the arrangement geometry which presents a high geometrical efficiency together with a relatively small electron counter loading, due to the primary π-mesons beam. The geometrical efficiency of the arrangement for the layout, shown in Fig.2, is presented in Fig.3. The distributions of primary and scattered π^--mesons and electrons in the plane of counters S_5 and S_6 are given in Fig. 4.

As a result of the investigation of the geometrical efficiency the following results have been obtained:

a) practically optimal parameters of the beam of primary π^--mesons (the parameters are presented above) are found;

b) a negligible dependence of the geometrical efficiency on the momentum spread in the primary beam $\Delta p/p \approx 1\%$ and on the momentum spread of the secondary electron $(\Delta p/p)_e \approx 2\%$ is obtained.

To evaluate the dependence of different experimental errors on the measurement accuracy of a root-mean-square electromagnetic radius of the π^--meson, events were generated according to the scattering law and taking into account the final electromagnetic radius of the π^--meson. Different experimental errors were introduced to the events generated in this way. The differential cross section, obtained after the geometrical corrections (weights) have been introduced, was processed by the method of least squares and the root-mean-square radius of the π^--meson was extracted. The events in an interval of transferred momenta from 160 MeV/c to maximum 192 MeV/c were analysed. The results of the investigation are presented in Tables I, II for the given radius 0.7 f .

As is seen from Tables, the uncertainty, dependent on the statistics, results in a fundamental contribution to the final error. Figure 5 shows the results of processing, by the least square method, the events of Table I. The solid line is a fit. For comparison a theoretical curve for $r_\pi = 0$ is given.

The calculations indicate that it is possible to measure the electromagnetic radius of the meson as roughly equal to 0.7 f with an accuracy of 0.1 f , provided that the calibration measurements are made with an accuracy of 2-3%.

5. Radiative Corrections

In order to find the electromagnetic radius of the π-meson at 0.6 - 0.7 fermi with a 50 GeV π-meson initial energy, it is necessary to measure the difference between the experimental cross section and the cross section of a point charge of the order of 10-15% of the cross section value. It is well known that at high energies radiative corrections become significant. In this connection radiative corrections should be calculated.

Radiative corrections have been calculated[5] in the Laboratory of Theoretical Physics of JINR.

Let us neglect the two-photon exchange diagrams and the corrections due to the meson current, then the formula for the cross section taking into account the radiative corrections of the lower order is as follows:

$$d\sigma / dq = d\sigma_B / dq \left(1 + \frac{\alpha}{\pi}\delta\right) F^2(q^2),$$

where $d\sigma_B / dq$ - is the differential cross section without taking into account strong interactions, δ -is the radiative correction, α- is the thin structure constant.

The value δ is calculated with an accuracy of the first-order terms. For δ the following expression can be written:

Table 1.

$P = 50$ GeV/c, $\Delta p/p = 0.5\%$, $\sigma_x = \sigma_y = 1.5$ cm.,
$\Delta\theta = 1.5$ mrad, $q_{min} = 160$ MeV/c, $q_{max} = 192$ MeV/c,
$\sigma_t = 0.47$ μbn.

M	N	η%	r_π	σ_{r_π}
561	384	5.5	1.00	0.073
1299	922	5.1	0.80	0.065
1841	1301	5.2	0.75	0.059
2629	1861	5.2	0.71	0.054
4197	2977	5.1	0.68	0.045

M – the number of played events
N – the number of detected events
η – the ratio of the number of primary π^--mesons in the electron counter, to M.

Table II.

	Statistical error	Random error in measurement of momenta of primary and secondary π-meson	Systematic error in measurement of momentum of primary π-meson	Systematic error in measurement of momentum of secondary π-meson	System. error in nomalizing
	3000 events	1%	0.1%	0.1%	1%
Error in r_π	0.05 f	0.02 f	0.025 f	0.014 f	0.025 f

$$\delta = \delta_{el} + \delta_{inel} ,$$

where δ_{el}- is the contribution to the radiative correction of the diagrams without real bremsstrahlung photons, δ_{inel}- is the contribution taking into account the radiation of real photons.

Calculation if δ_{inel} correction, the value of which depends on the experimental apparatus resolution, was a matter of great difficulty.

The calculation has been made in two steps:

1. The experimental resolution of the apparatus resulting from the errors in the determination of the energy ΔE_e and in the determination of the secondary electron angle $\Delta\Theta_e$.

2. The experimental resolution of the apparatus resulting from the errors in the determination of the energy ΔE_π and of the secondary π^--meson angle $\Delta\Theta_\pi$.

For the kinematics, using ΔE_e and ΔE_π, the radiative corrections have been calculated in /6/.

The following results for primary π^--mesons at 50GeV and measurement accuracies of $\Delta\Theta$ =0.2 mrad have been obtained for the given two versions :

1. δ_{inel} gives the main contribution to the radiative correction. The typical values:

$$a\delta_{el}/\pi = +0.05; \qquad a\delta_{inel}/\pi = -0.12;$$

2. The radiative corrections depend weakly on the energy of the primary beam.

3. The radiative corrections are sensitive to the apparatus resolution. Thus, for π^- with a 50 GeV energy

at $\Delta E_e/E_e = 1\%$ $\qquad a\delta/\pi = -0.10$

at $\Delta E_e/E_e = 7\%$ $\qquad a\delta/\pi = -0.06.$

When the appratus resolution results from the parameters concerned with the π-meson at $\Delta E_\pi/E_\pi = 2\%$

at $\Delta\Theta = 0.2$ mrad $\qquad a\delta/\pi = -0.04$

at $\Delta\Theta = 0.1$ mrad $\qquad a\delta/\pi = -0.06.$

4. The contribution to the radiative correction of the diagrams, which can be modified by hadron interaction, is:

$$\alpha/\pi \cdot \delta_{hadron} = 0.008 .$$

There were no attempts to calculate hadron interactions.

Thus, main inaccuracy in determining the radiative corrections will result from an inaccurate study of the apparatus resolution.

It should be noted that all the calculations have been made for two scattering parameters whereas four parameters are measured in the experiment. It is not clear at present how to take into account the indicated four parameters when calculating the radiative correction.

Nevertheless, one can consider that additional errors, dependent on an inaccurate study of the radiative correction, are equal to (2-3)% of the point scattering cross section value. With a difference between the measured and theoretical cross sections roughly equal to 15% at 0.8 f , the conclusions of the previous paragraph will negligibly change.

6. Background and Spurious Triggering Statistics.

The process of π^0 -meson production, e.g.

$$\pi^- + p \to \pi^- + p + \pi^0$$

is one of the most obvious background processes, imitating $\pi^- - e^-$ scattering.

The probability of $\pi^- - e^-$ scattering imitation by this process can be roughly estimated as follows.

Let us consider that the spectra of secondary π^--mesons from $\pi^- p$ interactions are negligibly different from the spectra of π^--mesons from pp interactions. On this condition it is possible (using the data from paper /7/, which give the spectra of secondary π and p at high energies) to estimate the probability of π^--and π^0-mesons of arriving at a given solid angle with an energy in a definite range.

At 50 GeV/c for (25 - 37) GeV/c π^0 -mesons and (13-25)GeV/c π^- -mesons (an initial energy for mesons expected to be equal to 25 GeV/c) the indicated probability is equal to

$$W = W_{\pi^-} \cdot W_{\pi^0} = 10^{-3} \cdot 10^{-3} = 10^{-6}$$

in the solid angle at our set-up.

Taking into account the probability of conversion of the π^0-meson to the electron at 25 - 37 GeV/c $\approx 10^{-2}$, suppressions of inelastic events by anticoincidence counters $\approx 10^{-1}$ and selection ptobabilities by the kinematics $\approx 10^{-4}$ (after the analysis of the event by momenta and angles with the help of spark chambers), a total probability of deflection of such an event as $\pi^- e^-$-scattering on one incident π^--meson is equal to

$$W_0 = 10^{-7} \cdot W = 10^{-13}$$

and is a negligible value as well with the number of spurious triggerings per cycle (except selection by the kinematics)

$$N_{\text{spurious trig.}} = 5 \cdot 10^4 \cdot 10^{-9} = 5 \cdot 10^{-5}$$

as with the background level

$$\frac{N_{\text{backgr.}}}{N_{\text{val.}}} = \frac{5 \cdot 10^4 \cdot 10^{-13}}{5 \cdot 10^4 \cdot 1 \cdot 10^{-6}} = 1 \cdot 10^{-7}$$

For the reaction

$$\pi^- + p \to \pi^- + p + \pi^+ + \pi^-$$

an analogous probability W is equal (a spectrum similar to the proton spectrum from pp interactions is taken for one of π^- -mesons) to :

$$W = W^{(1)}_{\pi^-} \; W^{(2)}_{\pi^-} = 3 \cdot 10^{-1} \cdot 10^{-3} = 3 \cdot 10^{-4} ,$$

Taking into account the suppression by anticoincidence counters $\approx 10^{-1}$ and the selection probability by the kinematics $\approx 10^{-4}$, the total detection probability of this reaction is :

$$W_0 = 10^{-5} \; 3 \cdot 10^{-4} = 3 \cdot 10^{-9}$$

In this case the number of spurious triggerings per cycle (excluding by the kinematics) is

$$N_{spur.\ trig.} = 5 \cdot 10^{4} \cdot 3 \cdot 10^{-5} = 1.5$$

and the background level is

$$\frac{N_{backgr.}}{N_{val.}} = \frac{5 \cdot 10^{4} \cdot 3 \cdot 10^{-9}}{5 \cdot 10^{4} \cdot 1 \cdot 10^{-6}} = 0.003 \ .$$

Thus, the level of spurious triggerings for the last reaction is significant (taking into account 3–4 msec as the spark chamber fast operation and 0.5 sec as time dilitation, losses are $\approx$ 1%), the 0.3% background level is already a significant value.

A number of accidental triggerings of the set-up, when 5% of the primary beam penetrates into the shower counter and the resolution of the coincidence diagram is $\approx 10^{-8}$ sec, is mainly determined by sensitivity of the π^--meson counter, and is of the order of 0.1 - 0.5 of spurious triggerings per cycle.

Time Required at the IHEP Accelerator

On the assumption that

a) the primary π^--meson momentum is 50 GeV/c

b) the accelerator cycle = 10 sec

c) intensity per cycle = $5 \cdot 10^4$

d) H_2 length = 50 cm

e) the cross section in a (160 - 192) MeV/c interval is σ_t = 0.47 μ bn, the time required for obtaining 2500 events is 150 hours. Besides, further 150 hours are necessary to make calibration measurements.

The statistics obtained permit to measure the π -meson size 0.7 f , with an accuracy of $\approx$ 0.1 f .

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Received by Publishing Department
on November 11, 1969

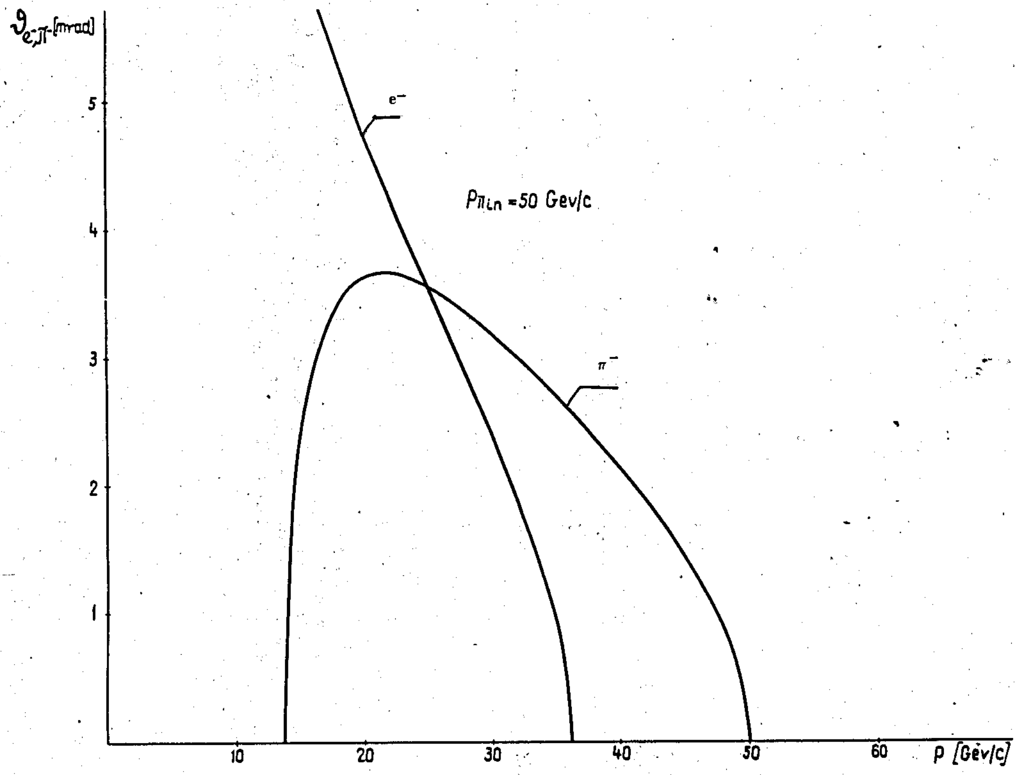

Fig.1. The kinematic angle-momentum dependences of the secondary π -meson and electron for a 50 GeV/c momentum of the primary π -meson.

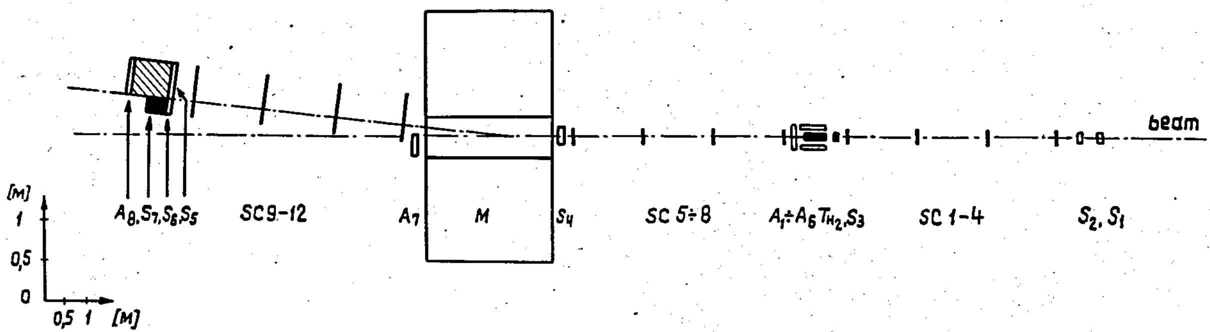

Fig.2. The experimental layout. S_1, S_2, S_3 – the monitor scintillation counters; S_4, S_5, S_6 – the scintillation counters to detect the π-meson and electron scattered; SC1 – SC12 – the spark chambers ; T_{H_2} – the hydrogen target; $A_1 - A_8$ – the anticoincidence counters; S_7 – the shower counter; M – the magnet.

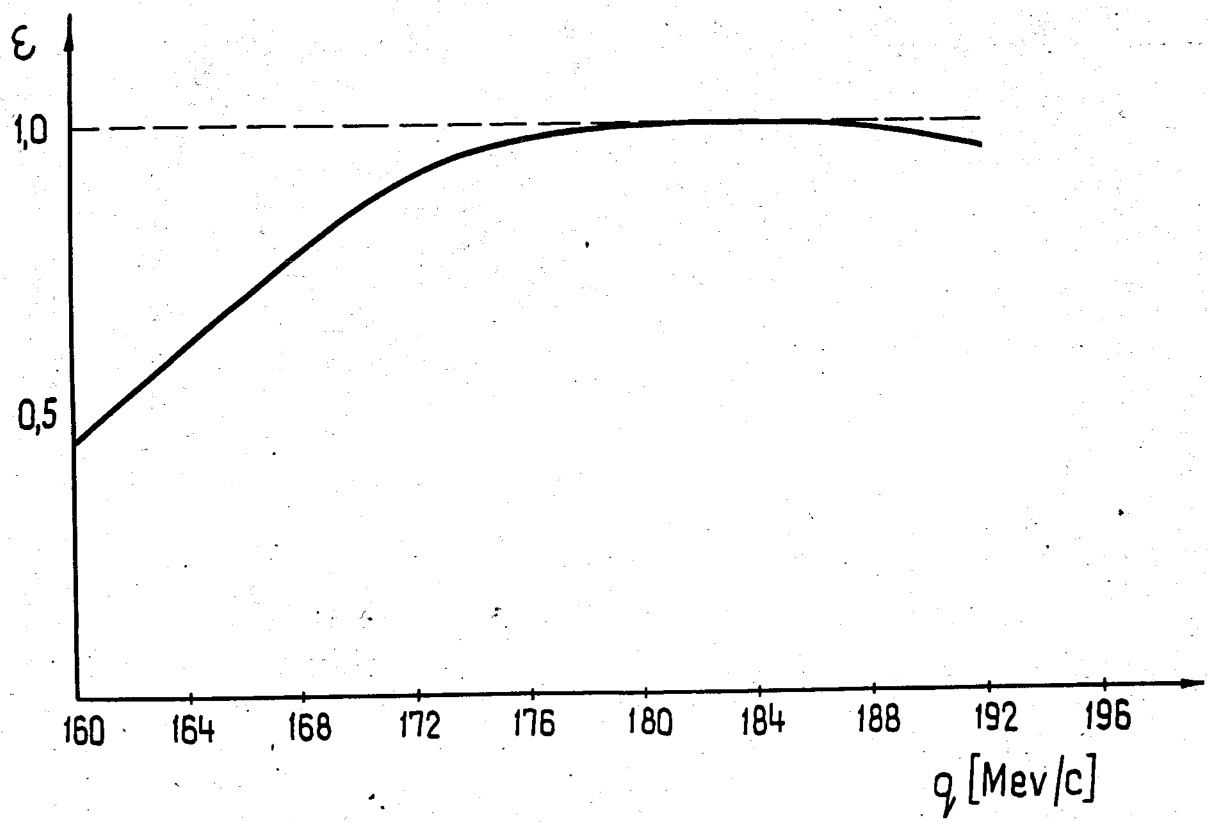

Fig. 3. The geometrical efficiency of the experimental set-up against transfer momenum q .

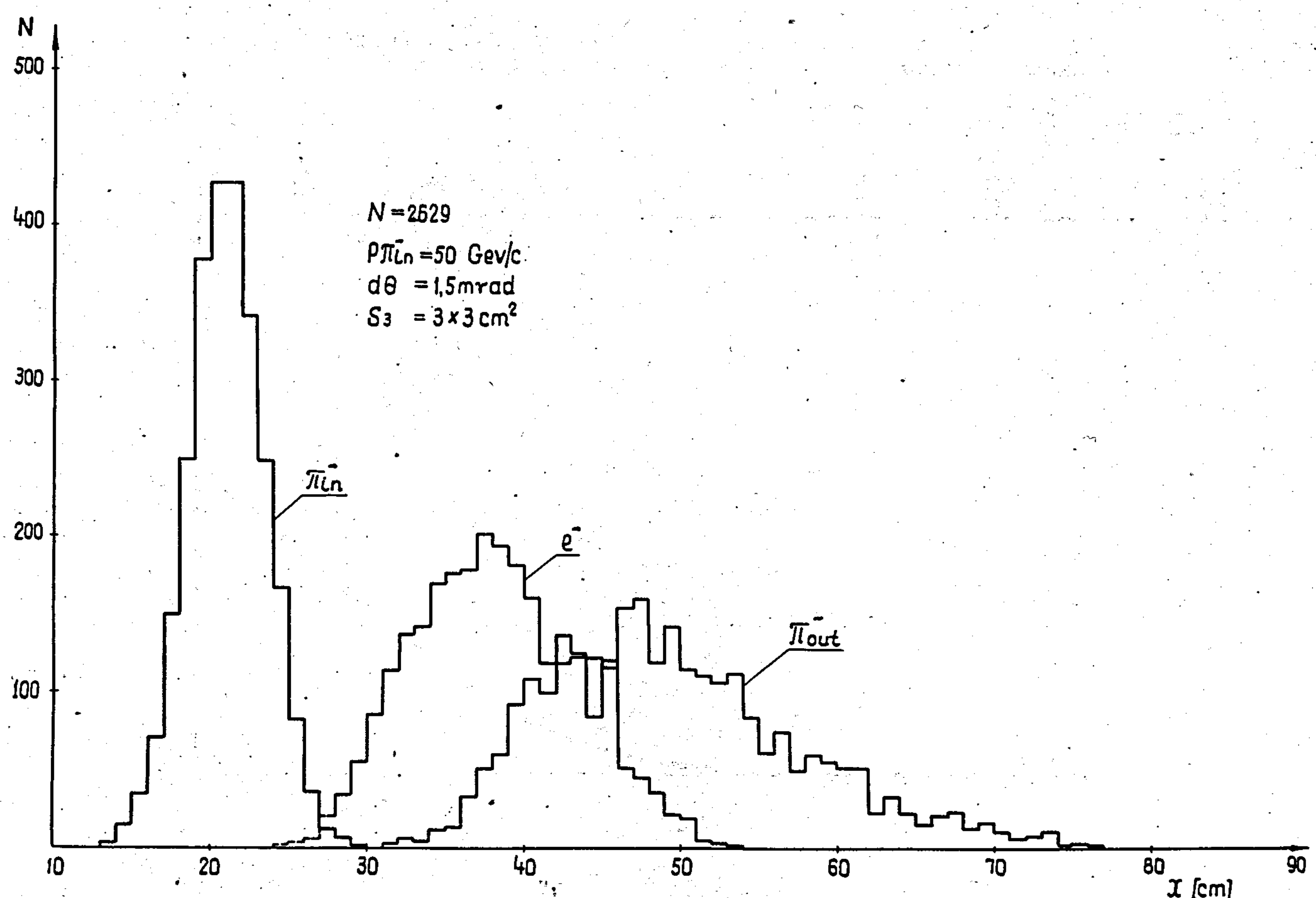

Fig. 4. The distributions of primary and scattered π -mesons and electrons in the plane of counters S_5 and S_6.

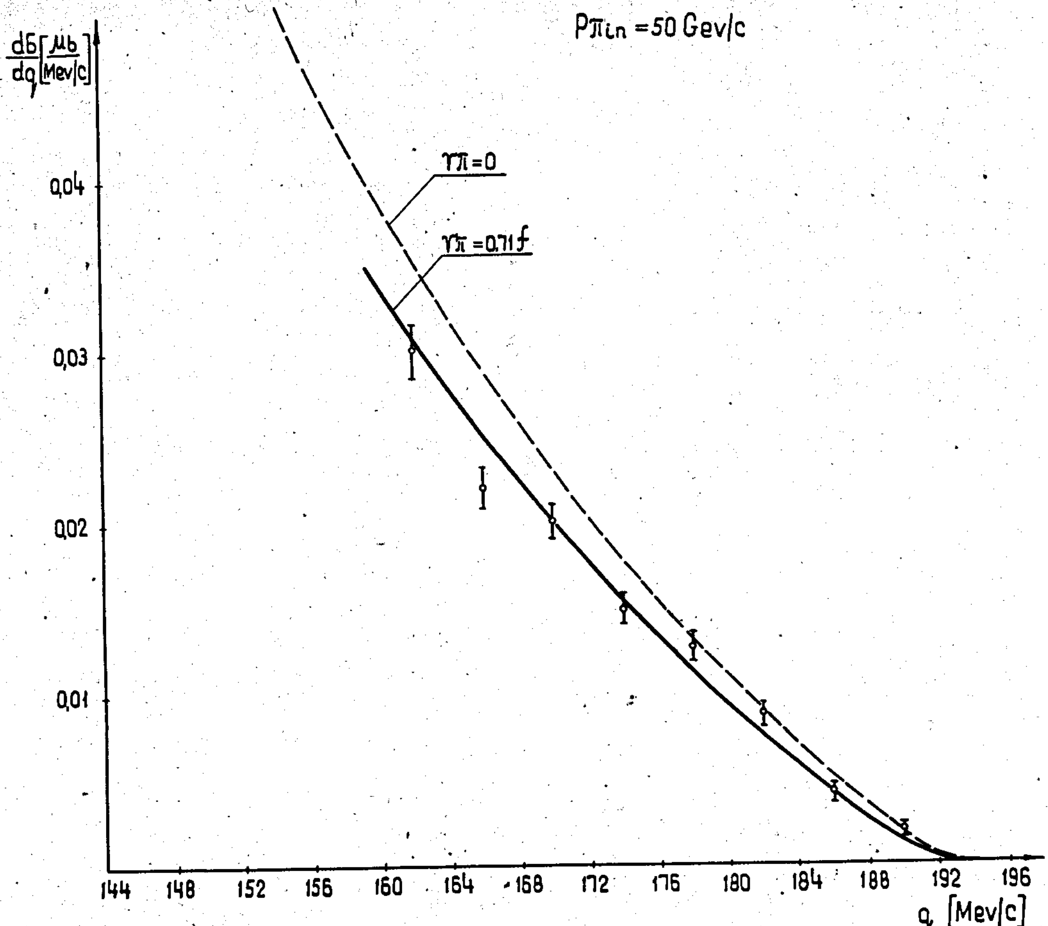

Fig. 5. The results of processing by the least square method. The dashed line is a theoretical curve for $r_{\pi} = 0$. The solid line is a fit curve for $r_{\pi} = 0.7\,f$.