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INVESTIGATION OF THE A_2 AND A_3 MESON PRODUCTION IN $\pi^- p$ INTERACTIONS AT A MOMENTUM OF 4.45 GeV/c

G.V. Beketov, S.M. Zombkovskij, B.S. Konovalov,
S.P. Kruchinin, Ya.M. Selektor and V.N. Shulyachenko

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1. INTRODUCTION

During the last year, the problem of the measurement of the quantum numbers of the A_2 mesons was given great importance. This problem is complicated by the demonstration of the splitting of the A_2 meson peaks[1]. The largest part of this work, in which an attempt was made to determine the quantum numbers of the A_2 meson, is based on the analysis of $A_2 \to \rho\pi$ decays. It can be fairly certainly established that this decay represents the principle A_2 decay. The difficulty occurs in the establishment of the spin and parity of the A_2 meson on top of the large background ($\sim$50-60%), of which the properties have still hardly been explored. In one work[2] the task was undertaken of calculating the angular characteristics of the background, in so far as it influences the density of points in the Dalitz plot. This allows one to say that up to now the spin of the A_2 meson is J = 2 and the parity is still not yet established.

In the present work, the total effective cross-section for A_2 and A_3 meson production in the reactions

$$\pi^- p \to A_2^- p, \qquad A_2 \to \rho^0 \pi^- \tag{1}$$

and

$$\pi^- p \to A_3^- p \tag{2}$$

at a momentum of 4.45 GeV/c is determined. We find values for the slope of the effective differential cross-section ($d\sigma/dt'$) for the production of a 3π system in various mass intervals. An analysis of the density distribution of the points in the Dalitz diagram and the angular distribution perpendicular to the decay plane of the A_2 meson was used. In this way the angular characteristics of the background and the influence of the Deck effect on the angular distribution was calculated.

2. THE EFFECTIVE MASS SPECTRUM

In order to analyse the reactions (1) and (2), about 300,000 photographs were examined; they were taken in a liquid hydrogen bubble chamber of 50 cm diameter with a π^- meson beam of 4.47 GeV/c from the ITEF proton synchroton. Events of the reaction

$$\pi^- p \rightarrow p\pi^+\pi^-\pi^- \qquad (3)$$

were selected, for which $P(\chi^2) \geq 0.5\%$, and the visible ionization of all tracks agreed with that expected for this reaction. A total of 2472 events of reaction (3) were obtained. The effective mass spectrum of the 3π system is given in Fig. 1. The interval of the A_1 meson ($950 \leq M_{3\pi} \leq 1150$ MeV) has been investigated by us[3]. In the total 3π system mass spectrum a maximum is clearly distinguished due to the A_2 meson; also a peak due to the A_3 meson $[\pi_A(1640)$ meson$]$ stands out weakly.

In Fig. 1 the 3π system mass spectrum for the decay via reaction (3) is displayed (as a hatched histogram) following the cuts: (a) events were selected for which the effective mass of at least one of the $\pi^+\pi^-$ systems lay in the ρ-meson region ($665 \leq M_{\pi^+\pi^-} \leq 865$ MeV); and (b) events with peripheral $\Delta^{++}(1236)$ isobar production were excluded [events with $1120 \leq M_{p\pi^+} \leq 1340$ MeV and $|t_{\Delta^{++}}| < 0.3$ (GeV/c)^2]. As we have demonstrated elsewhere[4], the exclusion of events forming a $\Delta^{++}(1236)$ isobar with $|t_{\Delta^{++}}| < 0.3$ (GeV/c)^2 is practically the same as excluding the whole peripheral background reaction $\pi^- p \rightarrow \Delta^{++}(1236)\pi^-\pi^-$. The ratio of the useful effect to no effect in the region of the A_2 meson amounts to $\sim 1:1$. The maximum of the A_2 meson corresponds to the mass $M_{A_2} \sim 1325$ MeV, the half-width to 120-150 MeV.

In Fig. 2 is displayed a mass spectrum of the 3π spectrum with the following cuts: (a) events with the smallest effective mass of the $\pi^+\pi^-$ system lying in the ρ meson band and the square of the four-momentum transfer of this system is such that $|t_{\pi^+\pi^-}| \leq 0.3$ (GeV/c)^2 were excluded; and (b) events with peripheral production of $\Delta^{++}(1236)$ isobars were removed by the method described above.

In Fig. 2b the effective mass spectrum of the 3π system from reaction (3) is seen, in which the effective mass of at least one of the $\pi^+\pi^-$ systems lies in the f^0 meson band.

In the distributions of Figs. 2a and 2b the A_3 meson peak is clearly recognized. The distribution of Figs. 2a and 2b were approximated by a Breit-Wigner curve for the A_3 meson, with the curve for invariant phase space below. The phase space curve was calculated within limits by a Monte Carlo method, making use of the experimental histogram. The results of the fit using the least squares method are drawn as a continuous line in Figs. 2a and 2b. For the mass and width of the A_3 meson, we find $M = 1672$ MeV, $\Gamma = 128$ MeV for the decay $A_3 \to \pi^+\pi^-\pi^-$, and $M = 1712$ MeV, $\Gamma = 128$ MeV for the $A_3 \to f^0\pi^-$ decay. The total production cross-section of the A_2 and A_3 mesons amounts to $\sigma_{A_2} = (60 \pm 7)$ μb; $\sigma[A_3^- \to (3\pi)^-] = (90 \pm 8)$ μb, and $\sigma[A_3^- \to f^0\pi^-] = (63 \pm 7)$ μb (all errors are statistical). The value found for the effective cross-section for $\sigma(A_3^- \to f^0\pi^-)$ is very sensitive to the form of the curve of the background fit used; thus in our opinion the hypothesis that the decay of the A_3 mesons takes place 100% through the $A_3^- \to f^0\pi^-$ channel is not excluded.

In Figs. 3a and 3b the distributions of the number of events of reaction (3) against the magnitude of $t' = |t - t_{min}|$ are represented graphically, where t is the square of the four-momentum transferred to the π^- mesons from the 3π system, and t_{min} the smallest possible value for this magnitude at the given mass value of the 3π system. The distribution of t' was found for the following mass intervals of the 3π system: (a) $975 \leq M_{3\pi} \leq 1275$ MeV; (b) $1275 < M_{3\pi} \leq 1375$ MeV; (c) $1375 < M_{3\pi} \leq 1575$ MeV; (d) $1575 \leq M_{3\pi} \leq 1775$ MeV; and (e) $1775 \leq M_{3\pi} \leq 1975$ MeV. The distribution was approximated by the exponential $dN/dt' \sim \exp(Bt')$ in the interval $0 < t \leq 0.8$ $(\mathrm{GeV}/c)^2$. By use of the maximum likelihood method we obtained the following values for the slope B: $B_a = 6.88 \pm 0.39$; $B_b = 3.77 \pm 0.56$; $B_c = 4.25 \pm 0.39$; $B_d = 3.95 \pm 0.39$; and $B_e = 3.38 \pm 0.47$ $(\mathrm{GeV}/c)^{-2}$.

The large value for the slope for the A_1 meson (975-1275 MeV) is consistent with the accepted assumption that the Deck effect supplies the main contribution to this mass region. At the large mass values a monotonic decrease of the slope with the mass of the 3π system is observed, suggesting the adoption of a contribution due to the peripheral diagram at large mass values of the 3π system. The monotonic lapse of the fall-off of the slope B with the 3π system mass is disturbed for the mass region of the A_2 meson; in this mass region a substantial decrease in the slope is established. For the A_2 meson production by exchange of poles belonging to the vacuum group, the effective differential cross-section $d\sigma/dt'$ must go to zero at $t' \to 0$. Due to the large background under the A_2 meson peak, and also to the statistical limitations, a minimum at small t' is not established.

3. ANGULAR DISTRIBUTIONS AND THE DENSITY DISTRIBUTION OF THE POINTS IN THE DALITZ PLOT IN THE A_2 MESON REGION

The usual method of determining the quantum numbers of a 3π resonance consists of the analysis of the density of points in the Dalitz plot, and the analysis of the differential angular distributions of the decay products of the resonance concerned. We carry out an analysis of the quantum number of the A_2 mesons with the help of the projections of the Dalitz plot and by use of the angular distribution between the direction of the normal of the decay plane of the A_2 mesons and the direction of the primary π mesons (angle θ) in the S-system of the A_2 mesons. The analysis was worked through for the quantum numbers $J^P = 2^+$ and 2^-. The projection of the Dalitz plot for the A_2 meson region on the $M^2_{\pi^+\pi^-}$ axis is represented in Fig. 4a. The selection of the events corresponds to the hatched histogram of Fig. 1. The theoretical curves were calculated for the quantum numbers 2^+ (continuous line) and 2^- (broken line) in accordance with Frazer et al.[5]. The calculated curves were normalized to the total number of events in the histogram. The value of χ^2 gives for the hypotheses of the quantum numbers 2^+ and 2^-: $\chi^2_{2^+} = 28.53$, and $\chi^2_{2^-} = 148.63$, for 12 degrees of freedom.

In Fig. 5 is shown the distribution of the number of events in the A_2 meson region against $\cos\theta$ (Fig. 5a) and from the control region (Fig. 5b). The control region was selected from both sides of the A_2 meson band, corresponding to the mass intervals $1225 < M_{\pi\rho} < 1275$ MeV and $1375 < M_{\pi\rho} < 1425$ MeV. The distributions for the control regions were summed, being compiled relative to $\cos\theta = 0$, in order to increase the statistical accuracy.

The control distribution was approximated to the linear function $a + b\,|\cos\theta|$. For the parameters a and b, the values a = 32.9 and b = 17 were found. Under the assumptions that (i) the background in the A_2 meson band possesses the same character as in the control band, and (ii) that the number of background events is equal to the total number of events in the control region, the lines in Fig. 5b were directly drawn for the quantum numbers 2^+ and 2^- (continuous line and broken line). The theoretical distribution in $\cos\theta$ has been taken from Berman et al.[6] and was indeed obtained by a simplified assumption about the A_2 meson production mechanism. For all cases the assumption is that the A_2 was produced by exchange of a pole belonging to the vacuum group, i.e. the P, P′ or ρ poles. By this means one supposes that one can attribute the largest contribution to the density matrix element ρ_{11} if the spin and parity of the resonance lies in the natural series (1^-, 2^+, 3^-, ...) or ρ_{00} when the spin and parity of the resonance is attributed to the series 1^+, 2^-, 3^+, ... Taking into account the decay of the resonance, we adopt the quantum numbers 2^-, in order that the $A_2 \to \rho^0\pi^-$ decay takes place with the least angular momentum. From the above assumption the expression for the angular distribution (after taking into account the background) assumes the following form:

$$W_{2^+}(\cos\theta) = N_1(1 - 3\cos^2\theta + 4\cos^4\theta) + (32.9 - 17|\cos\theta|),$$

$$W_{2^-}(\cos\theta) = N_2(1 - 2\cos^2\theta + \cos^4\theta) + (32.9 - 17|\cos\theta|),$$

where N_1 and N_2 are the normalization factors. The value for χ^2 for the hypotheses of the quantum numbers 2^+ and 2^- are $\chi^2_{2^+} = 12.7$ and $\chi^2_{2^-} = 63.0$ for 9 degrees of freedom.

We find the centre of gravity of the A_2 meson distribution at ∿ 1325 MeV. This value for the A_2 meson mass differs from the mean world value by about 20 MeV. The A_2 meson maximum depends on the experimental cuts over the fairly wide mass interval of ∿ 1290 to ∿ 1340 MeV. The discrepancy can be easily explained either by a small (∿ 1.5%) systematic shift of the incoming momentum, or by a systematic displacement in the magnetic field values, or through both these effects together. If one claims that the exact discrepancy in this work is due to a systematic effect and not through the absence of a light A_2 meson in our work and in some other experiments, then one can examine the angular distributions and the distribution of the points in the Dalitz plot for a light and heavy A_2 meson.

Although we have observed no "splitting" of the maximum of the A_2 mesons, the mass distribution was divided into two parts (at the position of the centre of gravity of the peak) and for each part the analysis of the quantum numbers was carried out. For the "light" (A_{2L}) meson and for the "heavy" (A_{2H}) meson we chose the mass range 1275-1325 and 1325-1375 MeV. In Figs. 4b and 4c one sees the projection of the Dalitz plots for the mass intervals of the A_{2L} and A_{2H} mesons. The value for the χ^2 for the hypotheses $J^P = 2^+$ (continuous line) is equal to $\chi^2_{2^+L} = 11.9$ for 10 degrees of freedom, and $\chi^2_{2^+H} = 24.4$ for 11 degrees of freedom; for the hypotheses $J^P = 2^-$, $\chi^2_{2^-L} = 29.2$ for 10 degrees of freedom, and $\chi^2_{2^-H} = 29.5$ for 11 degrees of freedom.

The angular distribution for the mass region of the A_{2L} and the A_{2H} mesons referred to $\cos\theta = 0$ were added, thus increasing the statistical accuracy. The distribution for the A_{2L} meson mass region is displayed graphically in Fig. 5c, and that of the A_{2H} in Fig. 5d. The value of χ^2 for the hypotheses $J^P = 2^+$ and 2^- gives $\chi^2_{2^+L} = 3.6$; $\chi^2_{2^+H} = 7.7$ and $\chi^2_{2^-L} = 17.7$, $\chi^2_{2^+H} = 46.1$ for 4 degrees of freedom. Excluding the Deck effect by the above method leads to the values $\chi^2_{2^+L} = 4.7$; $\chi^2_{2^+H} = 9.2$; $\chi^2_{2^-L} = 17.4$; and $\chi^2_{2^-L} = 45.3$ for 4 degrees of freedom. The corresponding distributions and the theoretical curves are displayed in Figs. 5g and 5h. The continuous line represents the hypothesis $J^P = 2^+$, the broken line the hypothesis $J^P = 2^-$.

Thus the analysis of spins and parity of the A_2 meson gives the quantum numbers $J^P = 2^+$, for the A_{2L} and A_{2H} mesons as well as for the "single" A_2 meson, in agreement with a series of other works[7)].

To conclude we thank V.U. Vladimiroky, G.K. Kliger and A.B. Kaidalov for numerous useful comments.

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Figure captions

Fig. 1 : Effective mass distribution of the 3π system from reaction (1). The hatched distributions are the events for which the lowest effective mass of the $\pi^+\pi^-$ systems lies in the ρ meson band [events with the production of $\Delta^{++}(1236)$ isobars with $|t_{\Delta^{++}}| < 0.3$ GeV/c were excluded].

Fig. 2 : The distribution of the effective mass of the 3π system from reaction (1).

a) Events for which at least one $\pi^+\pi^-$ system lies in the mass interval of the ρ meson and $|t_{\pi^+\pi^-}| < 0.3\ (\mathrm{GeV/c})^2$; thus events with production of $\Delta^{++}(1236)$ isobars with $|t_{\Delta^{++}}| < 0.3\ (\mathrm{GeV/c})^2$ are excluded.

b) Events for which the effective mass of at least one $\pi^+\pi^-$ system lies in the f^0 meson mass region.

Fig. 3 : Distribution of the number of events of reaction (1) against $t' = |t - t_{min}|$ for different mass intervals of the 3π system:

a) $975 \leq M_{3\pi} \leq 1275$ MeV
b) $1275 < M_{3\pi} \leq 1375$ MeV
c) $1375 < M_{3\pi} \leq 1575$ MeV
d) $1575 < M_{3\pi} \leq 1775$ MeV
e) $1775 < M_{3\pi} \leq 1975$ MeV.

Fig. 4 : Distribution of the number of events from the A_2 meson band ($1275 < M_{3\pi} < 1375$ MeV) against $M^2_{\pi^+\pi^-}$. The selection of events corresponds to the hatched histogram of Fig. 1. The theoretical curves refer to the hypothesis $J^P = 2^+$ (continuous line) and $J^P = 2^-$ (broken line).

Fig. 5 : Distribution of the number of events against cos θ:

a) for the control region ($1225 < M_{\rho\pi} < 1275$ MeV and $1375 < M_{\rho\pi} < 1425$ MeV);

b) for the A_2 meson region ($1275 < M_{\rho\pi} < 1375$ MeV);

c) for the A_{2L} meson region ($1275 < M_{\rho\pi} < 1325$ MeV);

d) for the A_{2H} meson region ($1325 < M_{\rho\pi} < 1375$ MeV);

e, f) for the control region and the A_2 meson region, excluding the events with $|t_\rho| < 0.5$ $(GeV/c)^2$;

g, h) for the A_{2L} and A_{2H} meson regions; events with $|t_\rho| < 0.5$ $(GeV/c)^2$ were excluded; the theoretical curves correspond to the hypotheses $J^P = 2^+$ (continuous line) and $J^P = 2^-$ (broken line).

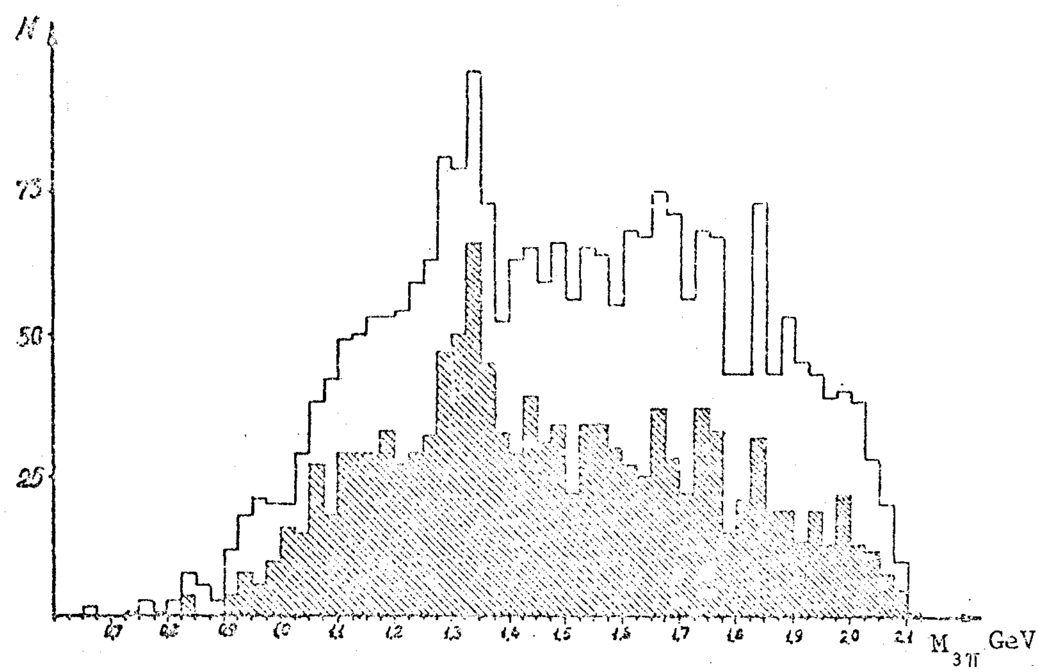

Fig. 1

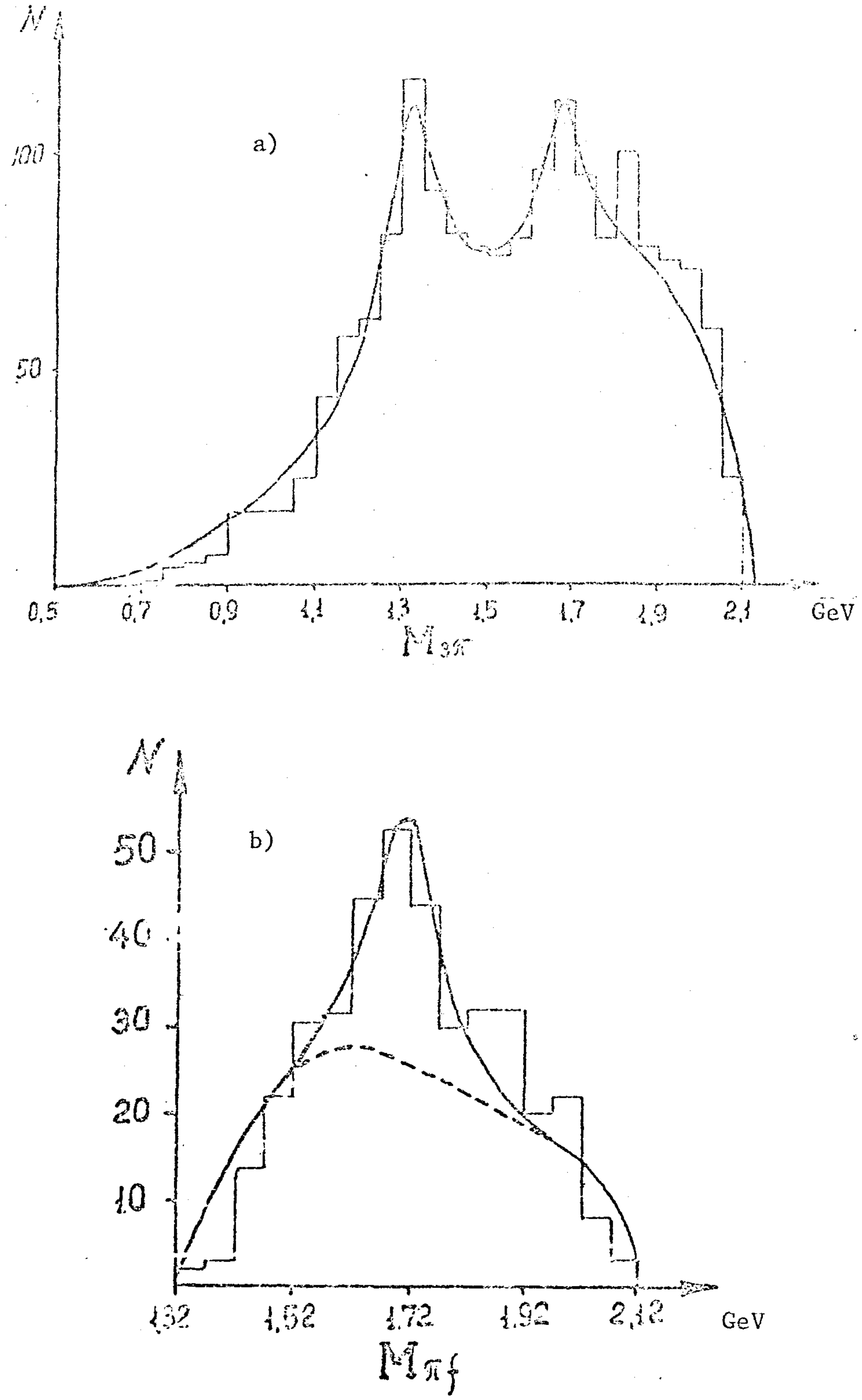
N
a)
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Fig. 2

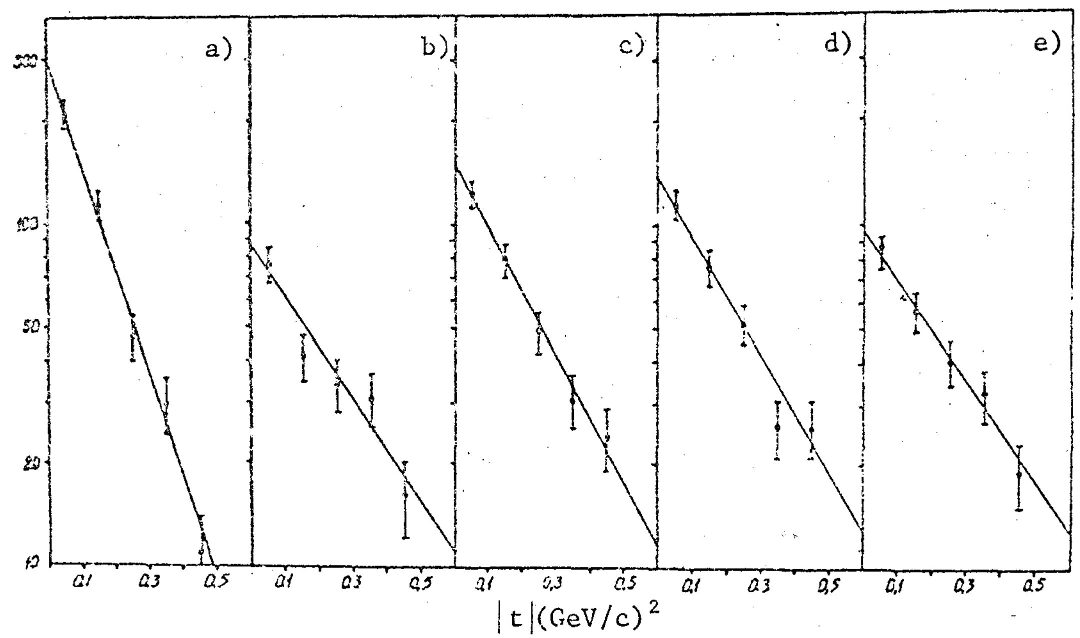


Fig. 3

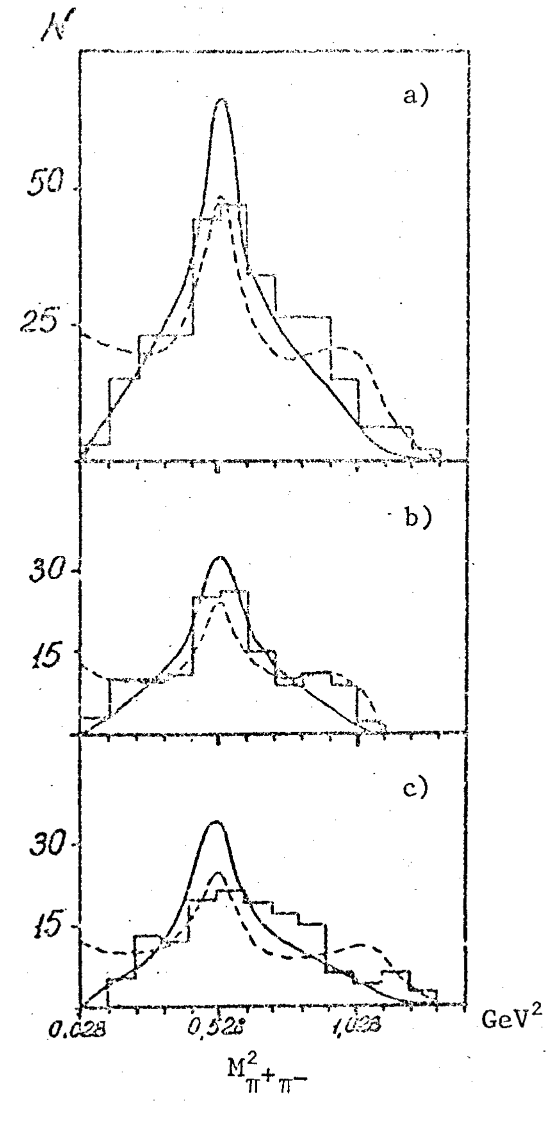
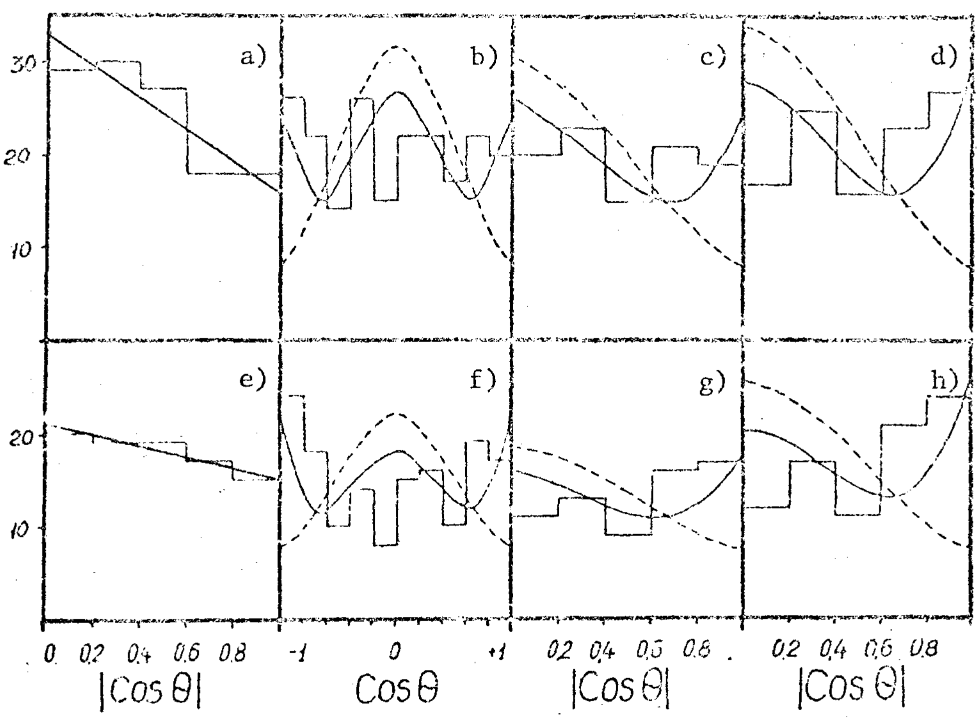


Fig. 4



a)
b)
c)
d)
e)
f)
g)
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10
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|Cos θ|
-1 0 +1
Cos θ
0.2 0.4 0.6 0.8
|Cos θ|
0.2 0.4 0.6 0.8
|Cos θ|

Fig. 5