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K^0_L-K^0_S TRANSMISSION REGENERATION ON HYDROGEN

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ABSTRACT

The energy dependence of the module and phase of the K_L^0-K_S^0 regeneration amplitude on hydrogen in the range of $14\div50$ GeV has been investigated at the Serpukhov 70 GeV accelerator. It has been established that the module of the modified regeneration amplitude decreases with increasing momentum as $2|f_{21}^0(p)|/p = (0.84 \pm 0.42)\cdot p^{-0.50\pm0.15}$ mb.

The amplitude phase is energy-independent and its mean value is $\varphi_{21}^0=-132^\circ\pm5^\circ$. The results obtained are compared with other experiments and with predictions of different theoretical models.

АННОТАЦИЯ

В экспериментах, выполненных на ускорителе на 70 ГэВ ИФВЭ в Серпухове, изучена энергетическая зависимость модуля и фазы амплитуды трансмиссионной регенерации K_L^0-K_S^0 на водороде в области $14\div50$ ГэВ. Установлено, что модуль модифицированной амплитуды регенерации уменьшается с увеличением импульса по закону $2|f_{21}^0(p)|/p = (0.84 \pm 0.42) \cdot p^{-0.50\pm0.15}$ мбн, а фаза амплитуды не зависит от импульса и ее средняя величина равна $\varphi_{21}^0 = -132^\circ\pm5^\circ$. Полученные результаты сравниваются с различными теоретическими моделями.

KIVONAT

Megvizsgáltuk a K_L^0-K_S^0 regeneráció abszolut értékének és fázisának energiafüggését hidrogénen, a szerpuhovi 70 GeV-es gyorsitó segitségével a 14-50 GeV tartományban. Megállapitottuk, hogy az abszolut érték és impulzus hányadosa a

$$2|f_{21}^0(p)|/p = (0.84 \pm 0.42) \cdot p^{-0.50\pm0.15} \text{ mb}$$

összefüggés szerint csökken, mig a fázis független az energiától: $\varphi_{21}^0=-132^\circ\pm5^\circ$. A kapott eredményt összevetettük más kisérletek eredményeivel és különböző elméleti jóslásokkal.

1. INTRODUCTION

As is well-known [1], the intensity of transmission /or coherent/ K_L^o-K_S^o regeneration on matter for incoming momentum p is defined by the coefficient $\rho(p) \equiv |\rho(p)| . \exp[i\phi_\rho(p)]$ which is equal to

$$\rho(p) = i\pi \cdot \frac{2f_{21}^o(p)}{p} \cdot \Lambda_S N . \rho'(p) \quad ; \qquad /1/$$

where

$$\rho'(p) = \{1-\exp[(i\Delta m/\Gamma s-1/2)\ell]\}/(1/2-i\Delta m/\Gamma s) \quad ; \qquad /2/$$

Λ_S is the K_S^o decay length in the laboratory, N is the matter density, $\Delta m = m_L - m_S$ is the K_L^o-K_S^o mass difference, Γ_S is the decay rate of K_S^o, $\ell = L/\Lambda_S$, L is the regenerator length, and

$$f_{21}^o(p) \equiv |f_{21}^o(p)| \exp[i\varphi_{21}^o(p)] = \frac{1}{2}[f^o(p) - \overline{f^o}(p)] \qquad /3/$$

is the transmission regeneration amplitude which is equal, by definition, to the semidifference of the K^o and $\bar{K}^o$ forward scattering amplitude on nuclei.

Of particular interest is the study of K_L^o-K_S^o regeneration on hydrogen at high energies since results of such an experiment can be used as a crucial check of basic theoretical models which predict an energy behaviour of the K_L^o-K_S^o regeneration amplitude on protons based on dispersion relations /DR/ [5-7] or complex angular momentum /CAM/ models [8-10].

In the CAM models the scattering amplitude is represented usually as a sum of the partial amplitudes each of which corresponds to exchange between particles by a pole with a certain set of quantum numbers.

In particular, only the poles ω and ρ contribute to the K^o_L-K^o_S regeneration amplitude on hydrogen. So if the Pomeranchuk theorem [11] is valid the f^o_{21} amplitude has the form of

$$\frac{f^o_{21}}{p} = B_\rho(o)\left[tg\frac{\Pi\alpha_\rho(o)}{2} + i\right].\left(\frac{1}{p}\right)^{1-\alpha_\rho(o)} - B_\omega(o)\left[tg\frac{\Pi\alpha_\omega(o)}{2} + i\right]\left(\frac{1}{p}\right)^{1-\alpha_\omega(o)} \qquad /4/$$

where $B_{\rho,\omega}(0)$ are the residue functions of the amplitude in the crossed channel at t=0, $\alpha_{\rho,\omega}(0)$ are the pole trajectories at t=0. If one takes into account that according to experimental data $\alpha_\rho(o) \sim \alpha_\omega(o) \sim \alpha(o) \sim 0.5$ $f^o_{21}(p)$ can be simplified:

$$\frac{f^o_{21}}{p} = -\sigma_{12}\left[tg\frac{\Pi\alpha(o)}{2} + i\right] .\left(\frac{1}{p}\right)^{0.5} \qquad /5/$$

where $\sigma_{12} = B_\omega(0) - B_\rho(0)$. From eq. /5/ the predictions [8,9] follow that 1/ the phase of the regeneration amplitude on protons does not depend on energy and is equal to

$$tg\varphi^o_{21}(p) = \frac{Imf^o_{21}(p)}{Ref^o_{21}(p)} = ctg\,\frac{\Pi\alpha(o)}{2} \ ; \qquad \varphi^o_{21} \simeq -135^o \ ; \qquad /6/$$

and 2/ the regeneration differential cross section at zero momentum transfer has the following energy dependence:

$$\left(\frac{d\sigma}{dt}\right)_{t=o} = \frac{\Pi\left|f^o_{21}(p)\right|^2}{p^2} \sim p^{2\alpha(o)-2} \qquad /7/$$

The contribution of other singularities slightly changes these predictions [8].

A number of CAM models give other predictions for the phase φ^o_{21} and $(d\sigma/dt)_{t=0}$ in the case of the Pomeranchuk theorem violation. From these predictions it follows that the phase φ^o_{21} is a function of energy and the differential cross section has a more complicated dependence on the kaon momentum than eq. /7/ with a minimum in the region 50-100 GeV/c. [8,9]

The DR [5,7] predictions for the regeneration amplitude on hydrogen in the case the Pomeranchuk theorem is valid are close to those for CAM, and in the case of its violation they are essentially qualitative.

The imaginary part of the hydrogen regeneration amplitude is related by the optical theorem to $\Delta\sigma(p)$, the difference of the total K^o and $\bar{K}^o$ cross sections on protons, and by means of isospininvariance to the difference of the total

K^+ and K^- cross sections on neutrons as well

$$2\,\mathrm{Im}\, f^{o}_{21}(p)/p = \frac{1}{4\Pi}\left[\sigma_T(K^o p)-\sigma_T(\overline{K^o}p)\right] = \frac{1}{4\Pi}\left[\sigma_T(K^+n)-\sigma_T(K^-n)\right] \qquad /8/$$

Due to this fact, it is possible in an original way to measure the difference of the total cross sections of kaon-antikaon interactions and thereby, independently of direct measurements of these cross sections, to study their asymptotic behaviour at $p\to\infty$ and also to investigate some anomalies of the cross sections in the preasymptotic region.

In particular, according to the simplified CAM model[8], from eqs. /5/ and /8/ it follows that

$$\Delta\sigma(p) \sim p^{-0.5} \qquad /9/$$

Experimentally, one can determine the module and phase of the K^o_L - K^o_S regeneration coefficient by studying the interference phenomena in the intensity of CP-violating $K^o_L \to \Pi^+ + \Pi^-$ decays and normal $K^o_S \to \Pi^+ + \Pi^-$ decays behind the hydrogen target placed in a K^o_L beam. The number of such decays can be described by the formula

$$\frac{d^2N}{dpdt}(p,t)\Delta p\Delta t = M_H . S(p) . \varepsilon(p,t) . \Gamma_s(+-) . |\eta_{+-}|^2 . I_{2\pi} . \Delta p . \Delta t, \qquad /10/$$

where M_H and $S(p)$ are the number and the spectrum of K^o_L transmitted through the target respectively, $\varepsilon(p,t)$ is the apparatus detection efficiency, $\Gamma_S(+-)$ is the $K^o_S \to \Pi^+\Pi^-$ partial decay rate, $\eta_{+-} \equiv |\eta_{+-}| . \exp(i\phi_{+-})$ is the parameter of CP-violation in kaon decays, and $I_{2\pi}$ is the two-pion decay distribution described by the well-known interference formula

$$I_{2\pi} = \left|\frac{\rho(p)}{\eta_{+-}}\right|^2 e^{-\Gamma_S t} + e^{-\Gamma_L t} + 2\left|\frac{\rho(p)}{\eta_{+-}}\right| e^{-\frac{\Gamma_L+\Gamma_s}{2}.t} .\cos(\Delta m t + \Phi_\rho(p) - \Phi_{+-}) \qquad /11/$$

where Γ_L is the K_L decayrate and $\Phi_\rho(p) = \varphi^o_{21}(p) + \frac{\Pi}{2} + \arg \rho'(p)$. /12/

The time t elapsed in the K^o restframe is related to z, the K^o decay point measured from the downstream end of the hydrogen target, by $t = zm/p$.

All the values in formulae /10/-/12/ are either known or can be measured in the same experiment. Thus having measured the distribution of the number of two-pion decays for various momenta of incident kaons and having fitted them to formulae /10/, /11/, we can obtain $|\rho(p)|$ and $\phi_\rho(p)$ and then $|f^o_{21}(p)|$ and $\varphi^o_{21}(p)$ using eqs. /1/-/3/ and /12/, i.e. it is possible to find separately the energy dependence of the imaginary and real parts of the K^o-$\bar{K}^o$ forward scattering amplitude difference.

The present experiment has been carried out at the Serpukhov 70 GeV accelerator. Preliminary results [13] /about 600 dipion K^o - decays/ indicated a decrease of the total $\bar{K}^o$-K^o - nucleon cross sections difference with increasing momenta in the region from 14 to 42 GeV/c. This was a first evidence[13] for the K^+n total cross section rise in this energy region and gave a possible explanation of the cross section anomaly behaviour found at Serpukhov[14].

Further results[15] based on about 2000 dipion K^o_L and K^o_S decays, which were detected in a 6 m long decay volume, also showed that both the so-called modified regeneration amplitude $2|f^o_{21}(p)|/p$ and $\Delta\sigma(p)$ decreased with increasing momentum from 14 to 42 GeV/c. This result, together with the energy independence of the K^-n total cross sections in the same energy region[14], independently of the direct measurements[16] established the rise of the K^+n total cross sections if isospin invariance holds. In ref.[15] it is also shown that the phase $\varphi^o_{21}(p)$ is likely to be constant for these energies and has an average value of /-118 ± 13/°. To obtain more detailed information about $\varphi^o_{21}(p)$, measurements with higher statistics and a longer decay volume were required. These requirements were satisfied in the experiment where the interference in dipion decays of kaons was measured in a 9 m long decay volume and about 5000 $K^o_{L,S} \to \pi^+\pi^-$ decays were detected in the momentum range 14-50 GeV/c. Preliminary results of this experiment are reported in refs.[17,18].

Here we present the final results of the K^o_L - K^o_S transmission regeneration amplitude on hydrogen in the momentum range 14-50 GeV/c.

2. PERFORMANCE OF THE EXPERIMENTS

In order to carry out the experiments, we have constructed a channel of neutral particles looking to the acclerator internal target /aluminium, ϕ = 2 mm, 2 cm long/ at an angle of 1° with respect to the direction of primary proton motion. The beam was defined by a system of three steel rectangular collimators 8.5 m in full length. The horizontal and vertical divergences of the beam were ± 0.35 and ± 0.6 mrad respectively. A cleaning magnet with a field intensity of up to 1.8 T and an effective length of about 5 m and a 10 cm lead converter in front of it removed charged particles and photons from the beam. The transverse dimensions of the formed beam at the collimator exit were 36.8 /horizontal/ and 62.1 /vertical/ mm. A 4 m long volume filled with helium was installed between the last collimator and the target-regenerator. The distance from the internal target of the accelerator where kaons were produced to the targetregenerator was about 56 m or more than 20 mean decay lengths of K^o_S with a momentum of 50 GeV. The intensity of neutrons and K^o_L mesons in the beam were 3.10^6 and 8.10^4 per sec respectively, for 10^{11} protons striking the internal target.

The experiment has been carried out with a filmless spark chamber spectrometer[19/] /fig.1/ on-line with a BESM-3M computer performing the control of the apparatus, data acquisition and writing of information on magnetic tapes[20/]. Use was made of a spectrometric magnet M with an effective length and width of pole pieces 200 cm and 100 cm, respectively, and a gap height of 25 cm. A constant field was achieved within ± 1% at a gap width of 80 cm.

The spectrometer detected the known types of K^o decays into two charged particles $K^o_{\pi 2} \to \pi^+\pi^-$; $K^o_{\mu 3} \to \pi^\pm \mu^\pm \nu$; $K^o_{e3} \to \pi^\pm e^\pm \nu$; $K^o_{\pi 3} \to \pi^+\pi^-\pi^o$ which occurred behind the hydrogen target in the decay volume /DV/ filled with helium. The decay point was determined by trajectories of decay particles reconstructed with the help of 18 two-coordinate spark chambers /SC1-18/ with magnetostrictive readout[21/]. The chambers were installed in front of and behind the magnet in groups of three each. The momentum $\vec{P}_1$ and $\vec{P}_2$ was measured by the particle deflection in the magnet. Using the information about the trajectories of decay particles and their momenta one can calculate a number of kinematic variables such as $m_{\pi\pi}$ the invariant mass assuming that decay particles are pions, the angle Θ between the directions of the incident and outgoing kaons and some others. These variables are used to select specific decay modes during an off-line data analysis.

Performing the experiment, we used the so-called "crossing geometry"[22/] set-up when the trajectories of decay particles cross behind the magnet. The crossing geometry provided a good momentum and effective mass resolution of the spectrometer without essential losses in homogeneity of the detection efficiency along the decay volume.

The decay configuration was selected and the spark chambers were triggered by scintillation counter[23/] hodoscopes FI, FII, GI, GII consisting of two groups of four counters each to the left and to the right from the beam axis. The spectrometer was triggered when at least one of the counters in each group fired and there was no pulse from the counters A, A_L and A_R. To identify three-body $K^o_{\mu 3}$ and K^o_{e3} decays, muon and electron detectors were used. The muon detector[24/] consisted of two planes of scintillation counters and two sections

125 cm in length each of a cast-iron filter absorbing strong-interacting particles. The first plane of four scintillation counters was located between the filter sections and was connected in coincidence with the second one to decrease accidental counting rates of the detector. The second plane consisting of ten counters each 20 x 64 x 2 cm^3 in size was used as a muon hodoscope.

The electron detector /DE/[25] was composed of four "sandwich" type total absorption counters in which an electron-photon shower was developed and detected. Each counter had two indentical units assembled from 10 scintillator plates and lead plates between them 10 and 5 mm in thickness respectively, and with an area of 555 x 300 mm^2. A light flash was recorded by two FEU-65 photomultipliers mounted at the top and the bottom of each unit.

The digitized information about the fired muon hodoscope counter position and the pulse amplitude from the electron detector was transferred to the computer when triggering the spark chambers. This information was used to identify kaon decay modes. If a continuation of one of the reconstructed decay product trajectories hitted the fired muon detector counter, the event was classified as $K^o_{\mu 3}$. If the pulse from the electron detector exceeded a certain level and one of the trajectories of decay particles passed through the counter, the event was classified as K^o_{e3}.

As a regenerator, we used a 3 m long liquid hydrogen target[26] with a working volume 12 cm in diameter. The amount of hydrogen along the beam path was 21.3 g/cm^2. The mylar window thickness from each side of the target was 0.53 g/cm^2. For measurement without hydrogen, use was made of a vacuum volume /dummy/ whose length and window thikness were equal to those of the target itself.

The experiment has been performed at two positions of the target defining the length of the decay volume of about 6 m /geometry 1/ and 9 m /geometry 2/. The magnetic field in the spectrometer magnet was 1.05 T and 1.3 T for geometry 1 and 2 respectively. The positions of the setup elements, triggering logic and the magnetic field value were optimized by Monte-Carlo calculations. The effective region of the investigated K^o_L momenta was equal to 10-30 GeV/c and 20-40 GeV/c in geometry 1 and 2. The setup efficiency to $K^o_{2\pi}$ decays of various momenta was /5-20/% within the indicated momentum intervals.

During the data taking periods, the used intensity of the internal beam was $/1\text{-}3/\cdot 10^{11}$ protons per cycle with the burst length from 0.4 to 1.5 sec. Altogether we detected the following number of events /in thousands/ in measurements with the hydrogen target and the dummy, respectively: 240 and 80 /geometry 1/, 1500 and 500 /geometry 2/.

3. DATA ANALYSIS

The final data analysis has been performed by the same method for geometries 1 and 2. It involved the following main steps:

1./ geometrical reconstruction of V^o-events[27];

2./ statistical processing of reconstructed events;
choice of event selection criteria and decay channel selection;

3./ calculations of the spectrometer efficiency for different K^o-decay channels;

4./ fitting of the intensity of the observed $K^o_{2\pi}$ decays to formula /10/ and determination of the physical parameters.

After geometrical reconstruction, the following number of events /in thousands/ was written on secondary magnetic tapes for a statistical analysis: 145 /hydrogen/, 48 /dummy/ for geometry 1; 700 /hydrogen/, 200 /dummy/ for geometry 2. Three-body $K^o_{\pi 3}$, $K^o_{\mu 3}$, K^o_{e3} decays constituted the greater part of these events.

During the statistical analysis we studied the geometrical and kinematical properties of the events, indentified the kaon decay modes by means of the lepton detectors, analyzed the $K^o_{\mu 3}$ and K^o_{e3} background among the events identified as $K^o_{\pi 2}$, and investigated the $m_{\pi\pi}$ and Θ- resolution of the spectrometer vs the K^o momentum[28]. The analysis showed that the mass and angular resolution of the spectrometer is determined by the formulae

$$\sigma_m(p) = (2.06 + 0.058 \cdot p)\ \mathrm{MeV/c^2} \quad ; \qquad /13/$$

$$\sigma_{\theta^2}(p) = (0.0172 + 9.14 \cdot p^{-2})\ \mathrm{mrad}^2 \quad ; \qquad /14/$$

where p is the kaon momentum in GeV/c.

As previously[18], two-pion kaon decays have been selected among all V^o-events using three basic criteria: 1/ decay particles are not leptons, 2/ the invariant mass $m_{\pi\pi}$ is in the kaon mass region, and 3/ the angle Θ is close to 0^o. Taking into account the experimental resolutions, an event is identified as a $K^o_{\pi 2}$ decay if its invariant mass is in the interval $498\ \mathrm{MeV/c^2} - 3\sigma_m(p) \leq m_{\pi\pi} \leq$ $\leq 498 + 3\sigma_m(P)$ and $\theta^2 \leq 9\sigma_{\theta^2}(P)\ \mathrm{mrad}^2$.

For the events, which were candidates for two-pion decays, the $m_{\pi\pi}$ and θ^2-distributions contained a certain number of background events mainly due to inelastic interactions of beam particles in the target and three-body $K^o_{\mu 3}$, K^o_{e3} decays. A larger fraction of the last background events was subtracted with the help of the lepton detectors. The distributions obtained /see fig. 2 and 3/ were approximated with a good confidence level by the functions

$$N(m_{\pi\pi}) = A_1(p) + A_2(p) \cdot \exp\left[- \frac{(m_{\pi\pi} - \bar{m}_{\pi\pi}(p))^2}{2\sigma^2_m(p)}\right] ; \qquad /15/$$

$$N(\theta^2) = B_1(p)+B_2(p)\cdot\theta^2+B_3(p)\cdot\exp(-B_4(p)\cdot\theta^2) \; ; \; B_4(p) = \frac{1}{\sigma_\theta^2(p)} ; \qquad /16/$$

where A_{1-2}, B_{1-4} are constants for a given momentum interval. In these expressions the last terms determine the expected distribution of two-pion events and the first terms the background. In order to determine the final number of two-pion decays in each interval of the momenta under investigation the background is subtracted by extrapolation of the corresponding θ^2 - distributions from the region of large θ values where there are only background events, from the peak region where $K^o_{\pi 2}$ decays are concentrated. The total number of two-pion decays selected in such a way was equal to 2000 and 250 in measurements with and without hydrogen for geometry 1 and 5000 and 800 for geometry 2 respectively.

As was shown in the introduction, in order to study the energy dependence of $f^o_{21}(p)$ it is necessary to obtain a type /10/ distribution. With this aim all the observed two-pion decays were distributed over $/p_i, t_j/$ bins. Each bin contained $N_{ij} \pm \Delta N_{ij}$ events where the errors included background subtraction procedure uncertainties and statistical ones as well. The distributions representing the left-hand side of eq. /10/ were obtained for eight kaon momentum $/ p_i/$ intervals from 14 to 50 GeV/c. The first seven of them had a width of $\Delta p = \pm$ 2 GeV/c and the last $\pm$ 4 GeV/c. Inside each p_i interval the events were distributed over time intervals in the K^o rest frame with a step of $\Delta t = 5.10^{-11}$ sec.

In order to perform the fitting procedure, as is seen from the right-hand side of formula /10/, one should know the values of $\varepsilon(p, t)$, $S(p)$ and M_H.

The shape of the kaon momentum spectrum S(p) was found by $K^o_{\mu 3}$ and $K^o_{\pi 3}$ decays detected by the setup simultaneously with $K^o_{\pi 2}$. The spectrum was reconstructed[29/] by comparing the experimental and Monte-Carlo generated distributions of "true" and "false" energies of decay particles.

The detection efficiency $\varepsilon(p, t)$ of events was calculated[30/] by Monte-Carlo method using ~ 10 times larger number of events than that of the experimentally observed events. In these calculations we took into account the errors in measuring the track coordinates in the spark chambers, the spark chamber efficiency, the multiple scattering of particles in the setup material, and the geometrical reconstruction program efficiency.

The product $K_H = M_H \cdot \Gamma_S(+-) \cdot |\eta_{+-}|^2$ entering into eq. /10/ can be measured by two methods. By the first method one can calculate M_H using the number of $K^o_{\mu 3}$ $(K^o_{\pi 3})$ decays observed in the experiment and the detection efficiency of these modes. The values $\Gamma_S(+-)$ and $|\eta_{+-}|$ are taken from the tables[12]. The second method permits K_H to be determined entirely in the framework of this experiment. Use is made of $K^o_L \to \Pi^+\Pi^-$ decays detected in the measurements without hydrogen. The number of these decays is determined by the expression

$$N_{2\pi} = M_V \cdot \Gamma_S(+-) \cdot |\eta_{+-}|^2 \cdot \iint e^{-\Gamma_L t} \cdot S(p) \cdot \varepsilon(p,t)dpdt \qquad /17/$$

where the integral is known by Monte-Carlo and thus the product $K_V = M_V \cdot \Gamma_{S(+-)} \cdot |\eta_{+-}|^2$ can be fixed. The transition from K_V to K_H can be done assuming that the ratio of the total number of any type of kaon three--body decays /or all together/, observed in the measurements with and without hydrogen is equal to the monitor ratio M_H/M_V since the total cross sections are approximately constant and one can neglect the change of shape of S(p) going from empty to full regenerator.

In order to perform the fitting procedure of the observed intensities or two-pion decays by formula /10/, the least-square method was used[31]. The three quantities K_H, $R = |\rho(p)/\eta_{+-}|$ and $\varphi^o_{21}(p)$ were taken as free parameters. The parameter K_H remained free but the same for all momentum intervals. It was checked that the values of the K_H parameter obtained for each momentum interval separately within experimental errors coincided with each other and with the value determined from the measurement without hydrogen as described above. The errors of the final physical quantities in the case of data fitting by eq. /10/ with the three mentioned parameters turn out to be somewhat larger than in the case when only R and $\varphi^o_{21}(p)$ are chosen as free parameters however they contain already the systematical uncertainties in addition to the statistical ones. In particular, we take into account possible errors in the experimental parameters of weak interactions, the momentum spectrum of incident kaons and their monitoring.

The experimental distribution of the number of two-pion decays of K^o_L and K^o_S vs proper time and the results of fitting them by eq. /10/ with and without the interference term in eq. /11/ are shown in fig.4. As is seen, the no-interference hypothesis has a very low confidence level.

The best values of the R and $\varphi_{21}^{o}(p)$ parameters obtained as a result of the fitting procedure for geometry 1 and 2 are shown in fig. 5 and their weighted values are listed in table 1. Performing the fits, we have used the following values of the weak interaction parameters for the $K_L^o - K_S^o$ system:

$$\tau_S = 0.895 \cdot 10^{-10}\ \text{sec}, \qquad \Phi_{+-} = 42^o \ ; \qquad /18/$$

$$\Delta m = 0.54 \cdot 10^{-10}\ \text{sec}^{-1}, \qquad \tau_L' = 5.181 \cdot 10^{-8}\ \text{sec}.$$

It is seen from fig. 5 that within experimental errors the results of the two experiments are in good agreement. The errors for geometry 1 are larger than for geometry 2 especially for momenta higher than 30 GeV/c due to poor statistics and correlations between the R and $\varphi_{21}^{o}(p)$ parameters when studying interference in a short decay volume. In geometry 2 with increasing statistics and the decay zone length, the values of R and $\varphi_{21}^{o}(p)$ turn out to be practically independent of each other for all momentum intervals.

Using the information obtained without hydrogen, we have determined the value of $|\eta_{+-}|$ to be $/2.14 \pm 0.15/ \cdot 10^{-3}$ when the number of K_L^o, passed through the apparatus is calculated by the observed numbers of $K_{\mu3}^o$ and $K_{\pi3}^o$ decays. This value is close to the current world weighted value/12/ but differs from that of the experiments[32,33/]. Taking into account the discrepancies on this parameter existing in the world literature, we give in tables 1 and 2 the results of f_{21}^o -measurements for two values of $|\eta_{+-}|$ /see also[47/]/.

The modified regeneration amplitude $2|f_{21}^o(p)|/p$ and the differential cross section at t=0 $(d\sigma/dt)_{t=o}$ have been calculated for the weighted values of R as well as K_p^o and $\bar{K}_p^o$ total cross section differences using the formula

$$\Delta\sigma(p) = 8\Pi\,|f_{21}^o(p)/p| \cdot \sin\varphi_{21}^o$$

where $\varphi_{21}^o = -132^o \pm 5^o$ is the observed average value of the regeneration amplitude. These values are shown in figs. 6 and 7 and listed in table 1.

We have investigated the dependence of the regeneration amplitude phase on a possible change of the parameters /18/. It turns out that the possible change of the φ_{21}^o average value can be expressed by the formula:

$$\varphi^o_{21} = -132^o \pm 5^o + 70^o \cdot \frac{0.54\cdot 10^{10} - \Delta m}{0.54\cdot 10^{10}} + \qquad /19/$$

$$+ 108^o \cdot \frac{\tau_s - 0.895 \cdot 10^{-10}}{0.895 \cdot 10^{-10}} + (\Phi_{+-} - 42^o).$$

The influence of other weak interaction parameters on the value of φ^o_{21} is negligible.

Possible systematic errors of φ^o_{21} and $2|f^o_{21}(p)|/p$ due to the procedures of event selection and background subtraction have been investigated as well. These errors are equal to about ± 3° and ± 8 μb, respectively.

Finally we have determined the energy dependence of $(d\sigma/dt)_{t=0}$, $2|f^o_{21}(p)|/p$ and $\Delta\sigma(p)$ fitting the values of table 1 by the expression of the type $A \cdot p^{-n}$, where p is the kaon momentum, A and n are free parameters. The results obtained are given in table 2 and in figs. 6 and 7.

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

The results obtained in these experiment can be summarized in the following way:

1. The existence of the interference between two-pion decays of long-lived K^o_L - mesons and short-lived K^o_S - mesons regenerated in liquid hydrogen has been observed in a direct way. The module and the phase of the $K^o_L - K^o_S$ transmission regeneration amplitude on hydrogen have been investigated in the momentum region 14÷50 GeV/c.

2. The module of the modified regeneration amplitude and the differential cross section of the transmission regeneration decrease with rising momentum by the laws /5,7/ with the constants given in table 2. These facts are in agreement with the CAM model predictions[8] if the Pomeranchuk theorem is valid.

3. It has been established that the phase $\varphi^o_{21}(p)$ of the transmission regeneration amplitude is energy-independent in the region 14-50 GeV/c and its average value is equal to $\varphi^o_{21} = -132^o \pm 5^o$. Considering the world experimental data on the kaon regeneration[36] on hydrogen, one can see /fig. 6a/ that within error bars the phase $\varphi^o_{21(p)}$ is energy-independent /or weakly energy-dependent/ even in the energy region 1.5 ÷ 50 GeV/c where its mean value is

equal to $\overline{\varphi}^{o}_{21} = -133^{o} \pm 3.2^{o}$. The value of φ^{o}_{21} obtained by us is in good agreement with the value -129^{o} predicted[8] by the CAM model assuming the Pomeranchuk theorem being valid.

4. Thus the phase and the module of the $K^{o}_{L} - K^{o}_{S}$ regeneration amplitude on hydrogen rule out the possibility of a large violation of the Pomeranchuk theorem in kaon and antikaon scattering on protons discussed in the literature[46] in 1969-1971. Comparing our results with the predictions[8] one can see that $\Delta\sigma(\infty) < 0.2$ mb where $\Delta\sigma(\infty)$ is the total cross section difference of kaons and antikaons at infinite energy.

5. The crossing symmetry and analytic properties of the scattering amplitude impose some restrictions on the energy behaviour of its real and imaginary parts. Based on these properties one can show /see refs.[42-45]/ that if the module of the regeneration amplitude has a power energy dependence of the type $2|f^{o}_{21}(p)|/p \sim p^{-n}$ then the phase of this amplitude is energy-independent and equal to

$$\varphi^{o}_{21}\ \text{theor} = -\Pi\left(1 - \frac{1-n}{2}\right) \qquad /20/$$

Substituting in eq. /20/ the value of $p = 0.5 \pm 0.15$ obtained in our experiments /see table 2/, we find ω^{o}_{21} theor $= -135^{o} \pm 13^{o}$ which is in good agreement with the experimental value of φ^{o}_{21}. So the energy behaviour of the module and the phase of the regeneration amplitude observed in this experiment proves that independently of any theoretical model the amplitude itself really satisfies the conditions of the crossing symmetry and analyticity.

6. The $K^{o}p$ and $\bar{K}^{o}p$ total cross section differences determined from our data have the energy behaviour $\Delta\sigma = A \cdot p^{-n}$ with the constants A and n given in table 2. This result is in good agreement with the direct measurements of the differences of the isospin conjugated total cross sections of K^{+} and K^{-} on neutrons[16] /see fig.6/. One can use the agreement of these data for a quantitative check of the isospininvariance in the reactions involving K-mesons.

For example, at an incident momentum 50 GeV/c the value of $\Delta\sigma(50)$ of this paper differs from the corresponding value of ref.[16] by about 6% of any $\Delta\sigma$ and about 0.3% of any cross section involved.

The decrease of $\Delta\sigma(p)$ in the momentum range 10-50 GeV/c observed in this experiment and the energy independence of the $K^{-}n$ total cross section[14] in the same energy interval predicts the rise of the $K^{+}n$ total cross section which was independently observed in direct measurements[16].

Based on the established energy dependence of $\Delta\sigma(p)$, the validity of the Pomeranchuk theorem and taking into account the data[16] on the $K^{\pm}n$ total cross sections up to 55 GeV/c, one can predict an increase of the $K^{-}n$ total cross section already in the region 100-200 GeV/c. This was observed in a recent experiment[35].

In its turn, the energy behaviour of the $K^{\pm}n$ total cross section difference in the region 23-280 GeV/c observed in ref.[35] /see Table 2/ agrees well with our data in the overlapping momentum interval. Consequently one can expect that the energy dependence of the regeneration amplitude module and phase we observed on hydrogen is also valid for a wider energy range, at least up to about 300 GeV.

7. According to the simplified CAM model, one can determine the ω-pole trajectory at zero momentum transfer from the measurements of the transmission regeneration amplitude on hydrogen if the pole has a dominating contribution to the amplitude. As is seen from formulae /6/ and /7/, in this case the measurements of φ^{o}_{21} and $(d\sigma/dt)_{t=0}$ should give the same value of $\alpha(0)$. From our mean value of the phase it follows that $\alpha(0) = 0.47 \pm 0.05$ and from the energy dependence of the regeneration cross section $\alpha(0) = 0.48 \pm 0.14$ if $|\eta_{+-}| = 2.35 \cdot 10^{-3}$. Thus one can see that in the given energy region two independent methods of measurement of $\alpha(0)$ give consistent results which in their turn agree with $\alpha(0) \approx 0.5$ available in the literature[8,16].

It should be noted that the energy dependence of the regeneration differential cross section somewhat different from ours has been obtained in the region 1.5-10 GeV/c[34]. This leads to $\alpha(0) = 0.33 \pm 0.03$ while from the measurement of the regeneration amplitude phase in this region it follows that $\alpha(0) =$ $= 0.49 \pm 0.05$. Thus the authors of paper[34] conclude that there occurs a violation of the phase-energy relation predicted by the CAM model.

From our data there is no such evidence. Moreover, the calculations of $(d\sigma/dt)_{t=0}$ and φ^{o}_{21}, in which use is made of the general form of the f^{o}_{21} amplitude /4/ where the parameters of contributing ρ and ω poles determined from other experiments[41], show /see fig. 6/ a good agreement of all data on the hydrogen regeneration with the CAM model predictions.

8. Within the framework of the CAM models the increase of the K^{+} total cross sections observed at Serpukhov can be explained in a variety of ways[10]. These models give different predictions for the regeneration amplitude on hydrogen as well. Their comparison with our data show that within experimental errors preference should be given to the model which takes into account only the ω

and ρ contribution to the amplitude. Both the energy dependence of the regeneration cross section and the ratio of the real to the imaginary parts of the regeneration amplitude do not need more complicated models in which dipoles, complex-conjugated poles and other singularities are taken into account.

In conclusion we express our acknowledgement to Professors A.M.Baldin and A.A.Logunov for the continuous support and attention to these experiments.

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Table 1.

p, GeV/c	$R=\|\rho(p)/\eta_{+-}\|$	$-\varphi^{o}_{21}$, degree ($\Phi_{+-} = 42^{o}$)	$2\|f^{o}_{21}(p)\|/p$, μb		$(\frac{d\sigma}{dt})_{t=o}$, μb/(GeV/c)^2		$\Delta\sigma = \sigma_T(\bar{K}^{o}p)-\sigma_T(K^{o}p)$,	
			$\|\eta_{+-}\| \cdot 10^3$		$\|\eta_{+-}\| \cdot 10^3$		$\|\eta_{+-}\| \cdot 10^3$	
			2.35	2.14	2.35	2.14	2.35	2.14
14 - 18	1.60 ± 0.35	139 ± 20	219 ± 48	199 ± 44	97 ± 43	80 ± 35	2.04 ± 0.25	1.86 ± 0.24
18 - 22	1.49 ± 0.15	132 ± 13	173 ± 18	157 ± 16	60 ± 12	50 ± 10	1.61 ± 0.14	1.46 ± 0.13
22 - 26	1.74 ± 0.14	127 ± 11	181 ± 15	165 ± 14	66 ± 11	55 ± 9	1.69 ± 0.14	1.53 ± 0.13
26 - 30	1.68 ± 0.16	139 ± 12	161 ± 16	147 ± 15	52 ± 11	43 ± 9	1.50 ± 0.13	1.36 ± 0.12
30 - 34	1.80 ± 0.15	130 ± 12	162 ± 14	148 ± 13	53 ± 9	44 ± 8	1.51 ± 0.13	1.38 ± 0.12
34 - 38	1.65 ± 0.15	127 ± 16	142 ± 13	129 ± 12	41 ± 8	34 ± 6	1.32 ± 0.12	1.20 ± 0.11
33 - 42	1.32 ± 0.29	142 ± 29	109 ± 24	99 ± 22	24 ± 10	20 ± 8	1.02 ± 0.13	0.93 ± 0.12
42 - 50	1.46 ± 0.25	109 ± 34	116 ± 19	106 ± 18	27 ± 9	22 ± 8	1.08 ± 0.12	0.99 ± 0.11
14 - 50		132 ± 5						

Experimental data on the measurement of the $K^{o}_{L} - K^{o}_{S}$ transmission regeneration amplitude on hydrogen in the momentum interval p = 14 - 50 GeV/c.

Table 2.

p, GeV/c	Function	A	n	Comments, references
14 - 50	$2\|f^{o}_{21}(p)\|/p$, mb	0.77 ± 0.38	0.49 ± 0.14	this experiment, $\|\eta_{+-}\|\cdot 10^3 = 2.14$
-"-	-"-	0.84 ± 0.42	0.50 ± 0.15	$\|\eta_{+-}\|\cdot 10^3 = 2.35$
-"-	$(d\sigma/dt)_{t=o}$ $\mu b/(GeV/c)^2$	1234 ± 1202	1.02 ± 0.29	$\|\eta_{+-}\|\cdot 10^3 = 2.14$
-"-	-"-	1474 ± 1575	1.04 ± 0.32	$\|\eta_{+-}\|\cdot 10^3 = 2.35$
-"-	$\sigma_T(\bar{K}^op)-\sigma_T(K^op)$ mb	8.4 ± 3.2	0.55 ± 0.11	$\|\eta_{+-}\|\cdot 10^3 = 2.14$
-"-	-"-	9.7 ± 3.4	0.56 ± 0.10	$\|\eta_{+-}\|\cdot 10^3 = 2.35$
15 - 65	$\sigma_T(K^-n)-\sigma_T(K^+n)$ mb	12.1 ± 4.1	0.65 ± 0.10	16)
23 - 280	-"-	12.1 ± 5.9	0.57 ± 0.11	35)
15 - 280	-"-	6.8 ± 1.3	0.46 ± 0.05	16,35)
I.5-10	$(d\sigma/dt)_{t=o}$ $\mu b/(GeV/c)^2$	3255 ± 988	1.33 ± 0.24	34)
I.5-50	-"-	3274 ± 607	1.36 ± 0.06	34,18)

Energy dependence of the regeneration data and the total cross section difference approximated by the function of the $A \cdot p^{-n}$ type where p is the K^o_L momentum in GeV/c.

FIGURE CAPTIONS

Fig. 1. Experimental setup /top and side views/.
BEAM is the beam of incident K_L^0 mesons; MN1 and MN2 are the telescopes of the scintillation counters for monitoring the beam; V is the volume filled with helium.
The notations of other elements are given in the text.

Fig. 2. The $m_{\pi\pi}$ distributions: A-geometry 1; B-geometry 2. The events satisfying the condition $\theta^2 < 9\sigma_\theta^2(p)$ /see formula /12// for the given K_L^0 momentum are taken. The mean momentum in GeV is indicated in the right corner of each diagram. The solid line is the results of an approximation of the distribution by the type /13/ function; the dotted line is the background.

Fig. 3. The θ^2 -distributions of events where θ is the angle between the directions of flight of incident and outgoing kaons: A - geometry 1; B - geometry 2. The events for which the invariant mass satisfies the selection criteria of two-pion events are taken. The points are the result of approximation of the distribution by the type /14/ function; the broken line is the background. The mean momentum in GeV is indicated above each distribution. The distributions of all events, observed in the inverval 10-50 GeV in the measurements with /H_2/ and without /vacuum/ hydrogen, are also shown.

Fig. 4. The intensity of two-pion decays of K^0 mesons versus time in the K^0 rest frame observed in geometry 2 conditions. The curves are the result of an approximation of the experimental data by formula /10/, $\chi^2 = 51$ for 93 degrees of freedom /solid curve/; by formula /10/ without the interference term, $\chi^2 = 307$ /chain-dotted curve/; only $K_L^0 \to \Pi^+ + \Pi^-$ decays /dotted curve/.

Fig. 5. Comparison of the experimental data on the K_L^0-K_S^0 regeneration on hydrogen at various momenta in geometry 1 /O/ and 2/●/ conditions:

a/ value $R = |\rho(p)/\eta_{+-}|$
b/ value $\varphi_{21}^0(p)$

Fig. 6. Results of measurements of the phase /a/ and the module /b/ of the K_L^0 - K_S^0 transmission regeneration amplitude on hydrogen and the differential regeneration cross sections at zero four-momentum transfer /c/.

Symbols / ● / denote the results of this paper;
/ o / paper[34];
/ ▲ / paper[38];
/ □ / paper[39];
/ x / paper[40];

The mean phase, $\bar{\varphi}^{o}_{21} = -133^{o}$, is the broken line in fig. /a/. The solid line is the calculation by the complex angular momentum model when $f^{o}_{21}(p)$ is determined by eq. /4/ with the trajectory parameters taken from paper[41]; the chaindotted line is the same type of calculation but with the parameters of poles and cuts taken from paper[8].

Fig.7. The kaon-antikaon total cross section difference /●/: $\Delta\sigma_T = \sigma_T(\bar{K}^{o}p) - \sigma_T(K^{o}p)$ data of this paper; /o/ and /Δ/: $\Delta\sigma_T = \sigma_T(K^{-}n) - \sigma_T(K^{+}n)$ results of papers[16] and[35] respectively. The solid line is the approximation of the Serpukhov and FNAL data by $A\cdot p^{-n}$ /see Table 2/; the broken line is the same for the results of this experiment.

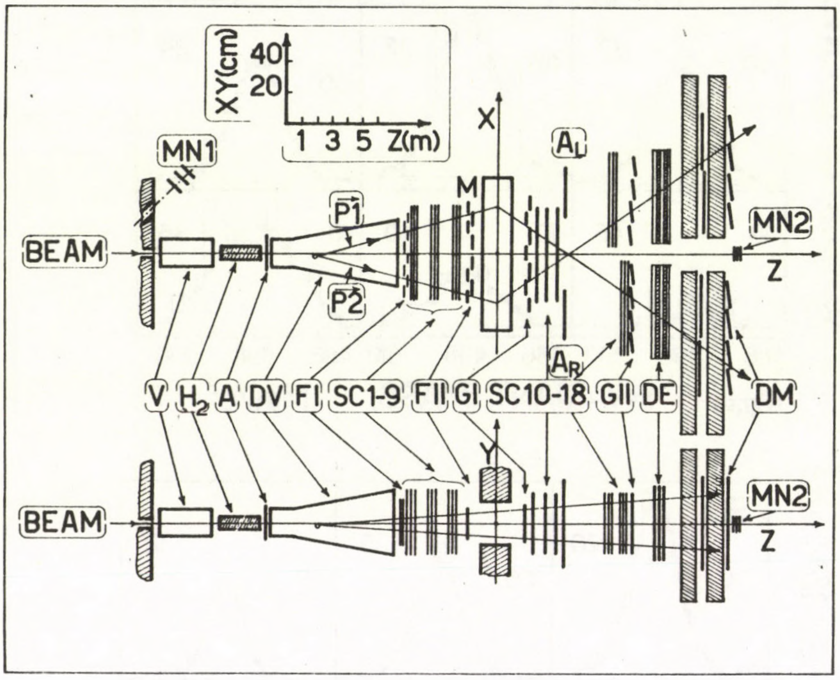

XY(cm)
40
20
1 3 5 Z(m)
MN1
BEAM
P1
P2
M
X
A_L
MN2
Z
A_R
V
H_2
A
DV
FI
SC1-9
FII
GI
SC10-18
GII
DE
DM
Y
BEAM
MN2
Z

Fig. 1.

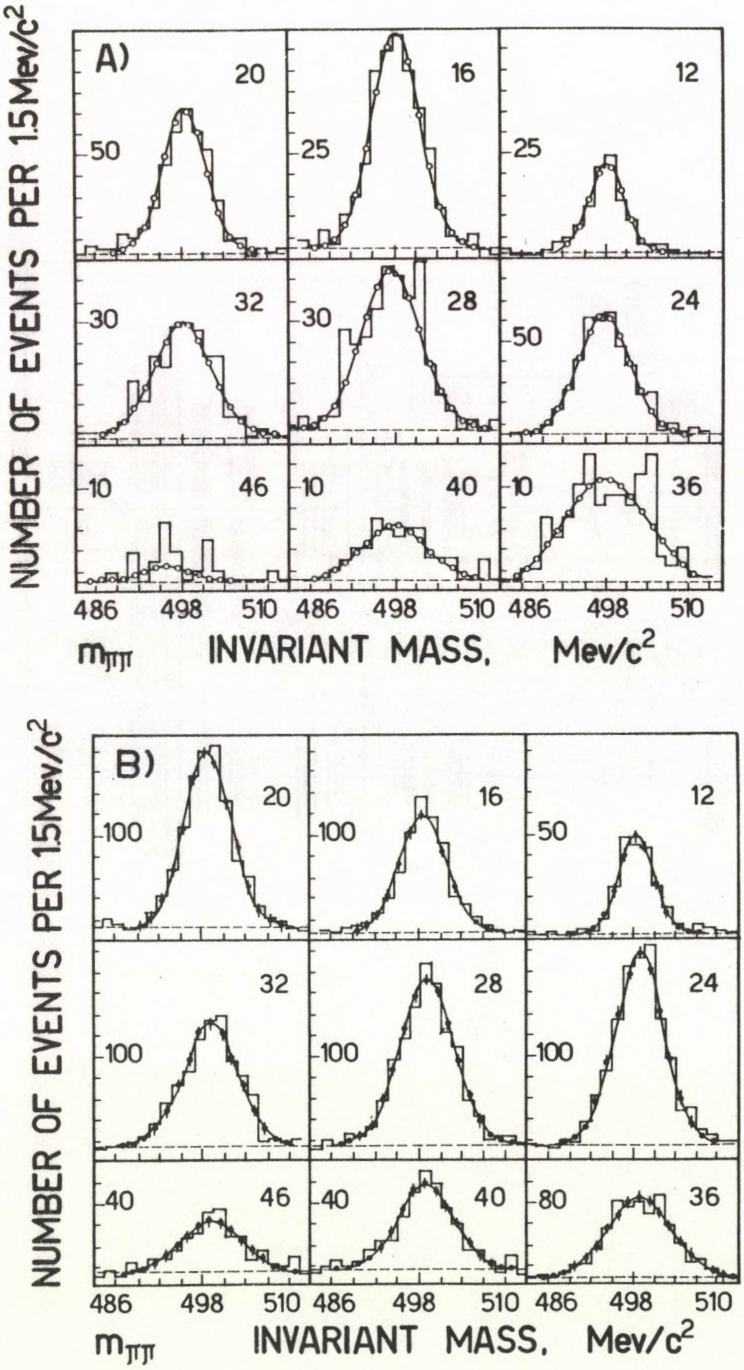

NUMBER OF EVENTS PER 1.5 Mev/c²
A)
20
16
12
50
25
25
32
28
24
30
30
50
46
40
36
10
10
10
486
498
510
486
498
510
486
498
510
mππ
INVARIANT MASS, Mev/c²
NUMBER OF EVENTS PER 1.5Mev/c²
B)
20
16
12
100
100
50
32
28
24
100
100
100
46
40
36
40
40
80
486
498
510
486
498
510
486
498
510
mππ
INVARIANT MASS, Mev/c²

Fig. 2.

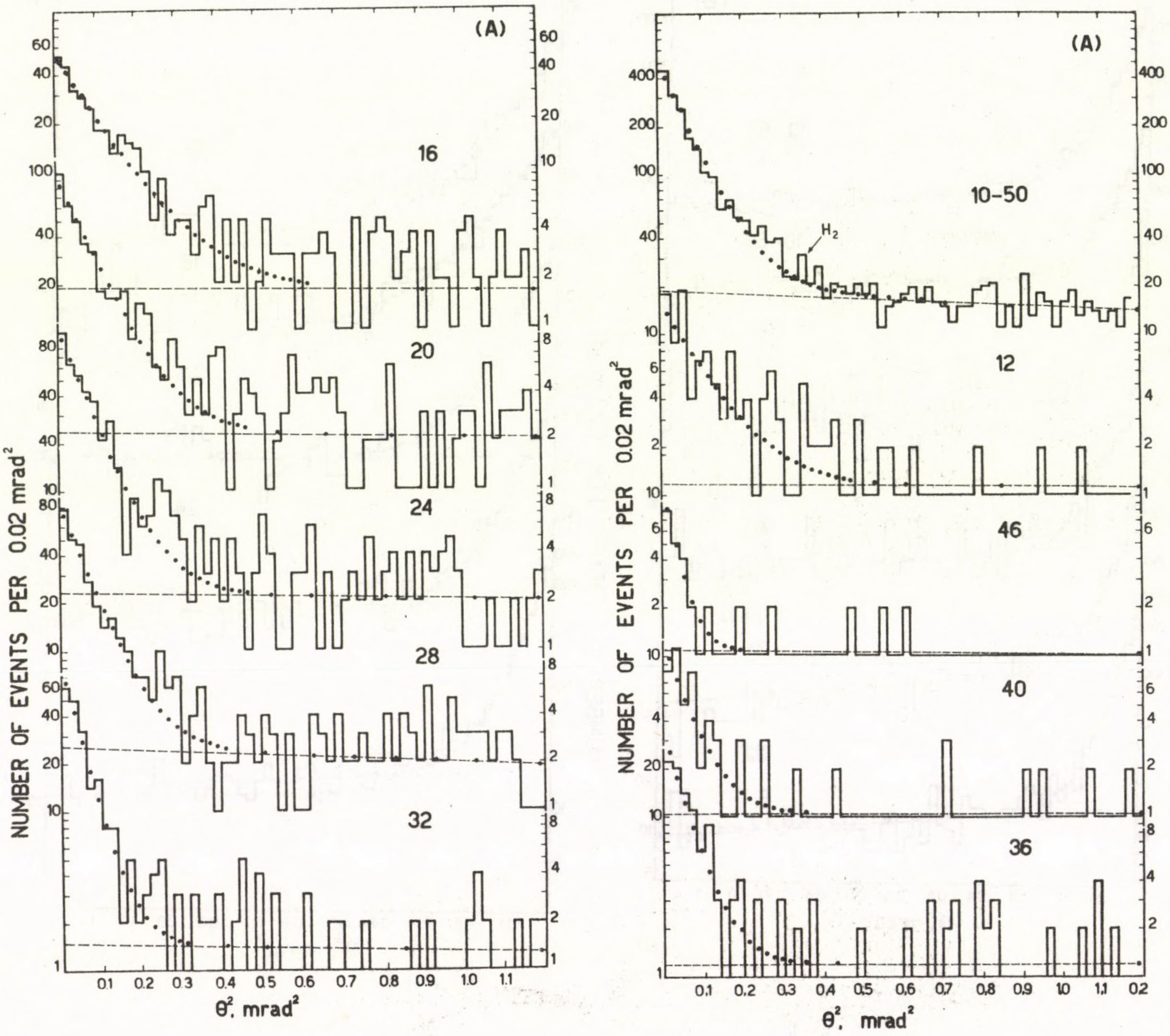

(A)
16
20
24
28
32
NUMBER OF EVENTS PER 0.02 mrad²
θ², mrad²
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
(A)
10-50
H₂
12
46
40
36
NUMBER OF EVENTS PER 0.02 mrad²
θ², mrad²

Fig. 3A.

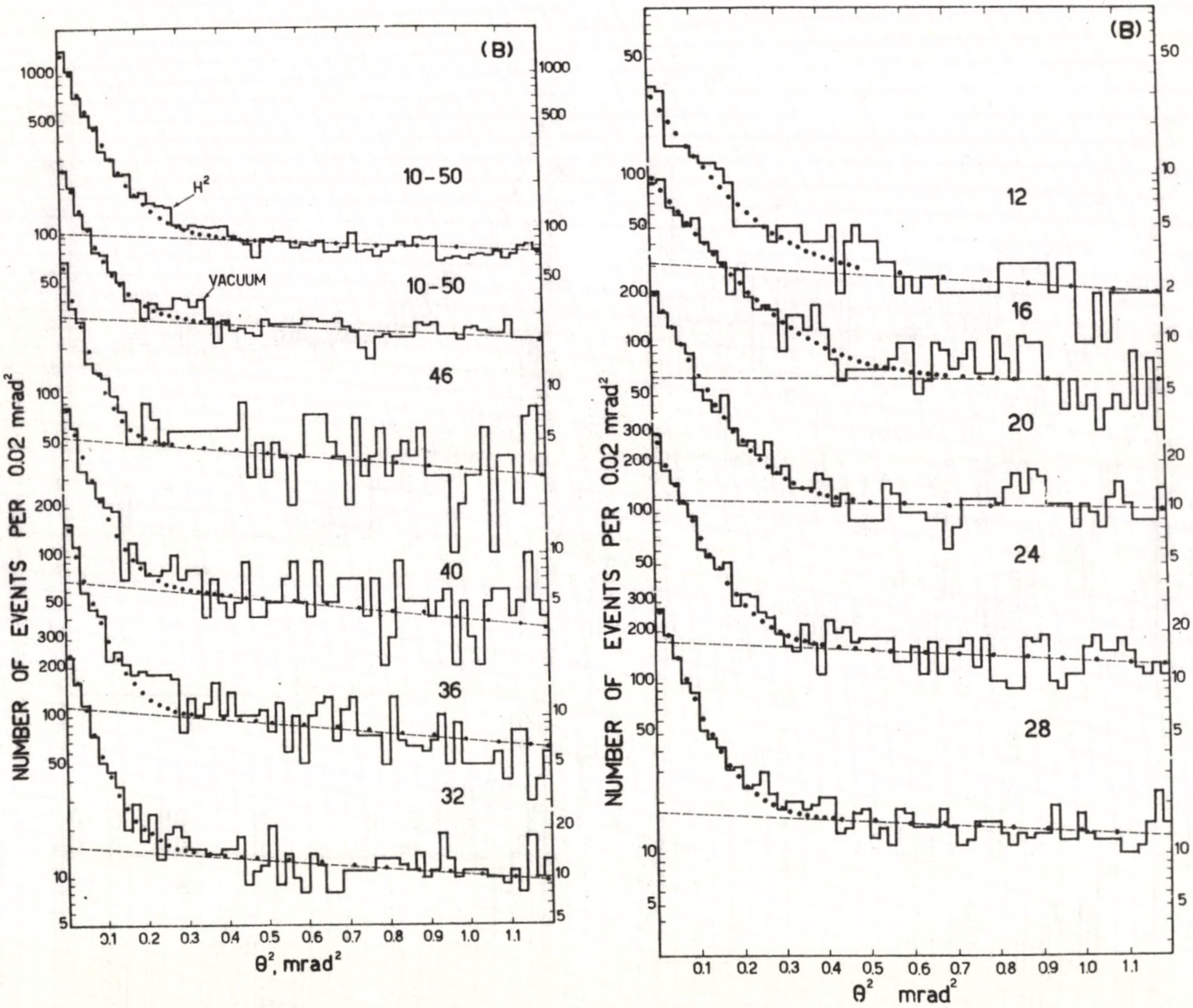

(B)
10-50
H²
10-50
VACUUM
46
40
36
32
NUMBER OF EVENTS PER 0.02 mrad²
θ², mrad²
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1
(B)
12
16
20
24
28
NUMBER OF EVENTS PER 0.02 mrad²
θ² mrad²

Fig. 3B.

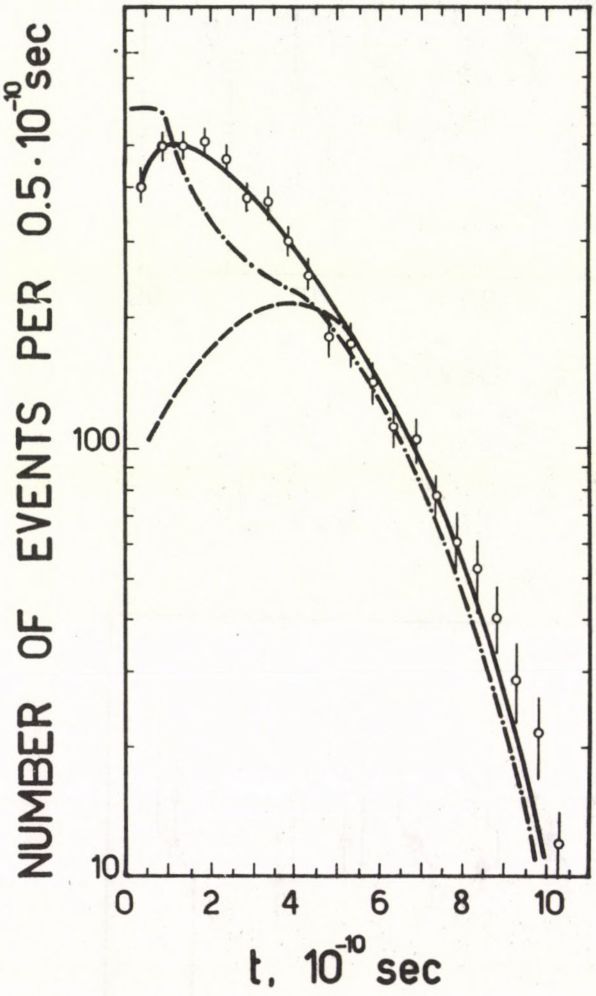


Fig. 4.

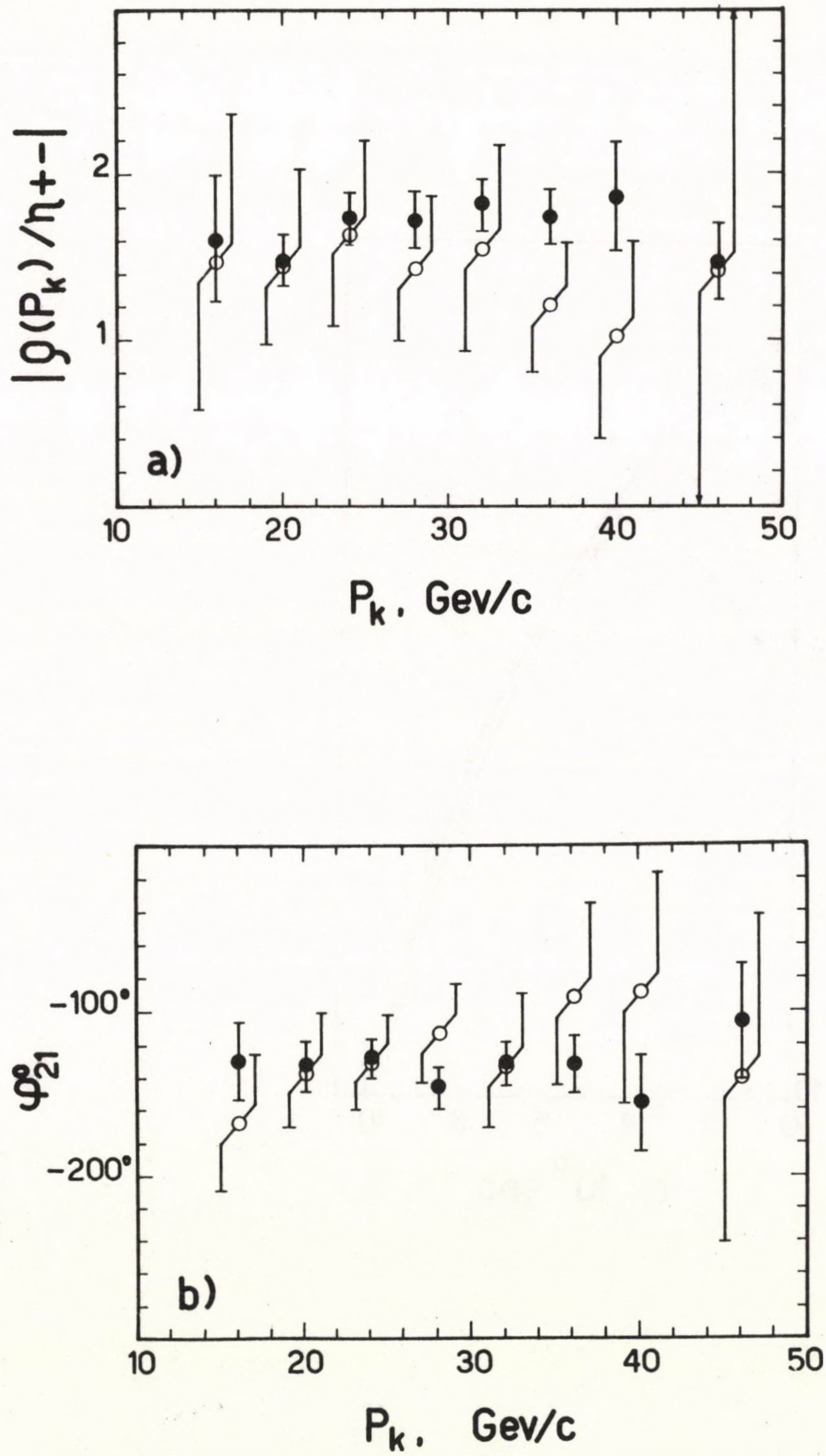
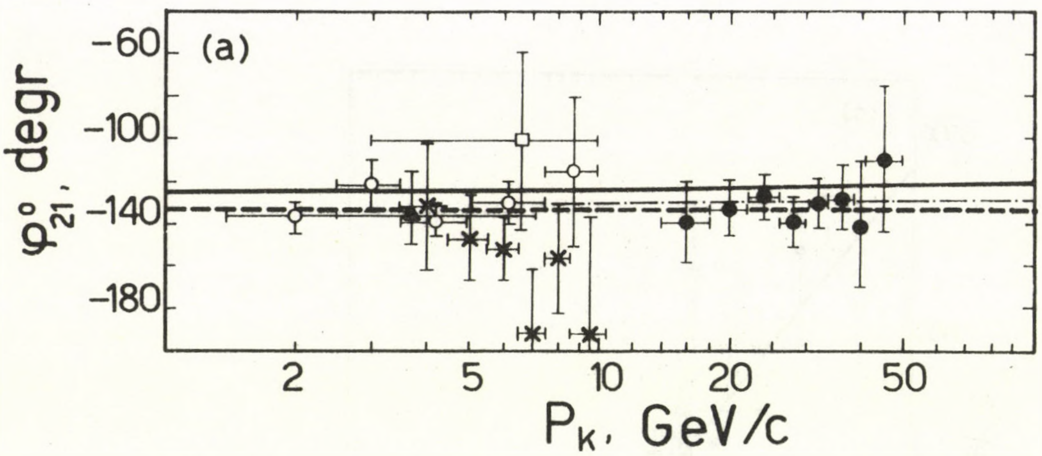


Fig. 5.


(a)
φ_{21}^{o}, degr
-60
-100
-140
-180
2
5
10
20
50
P_K, GeV/c

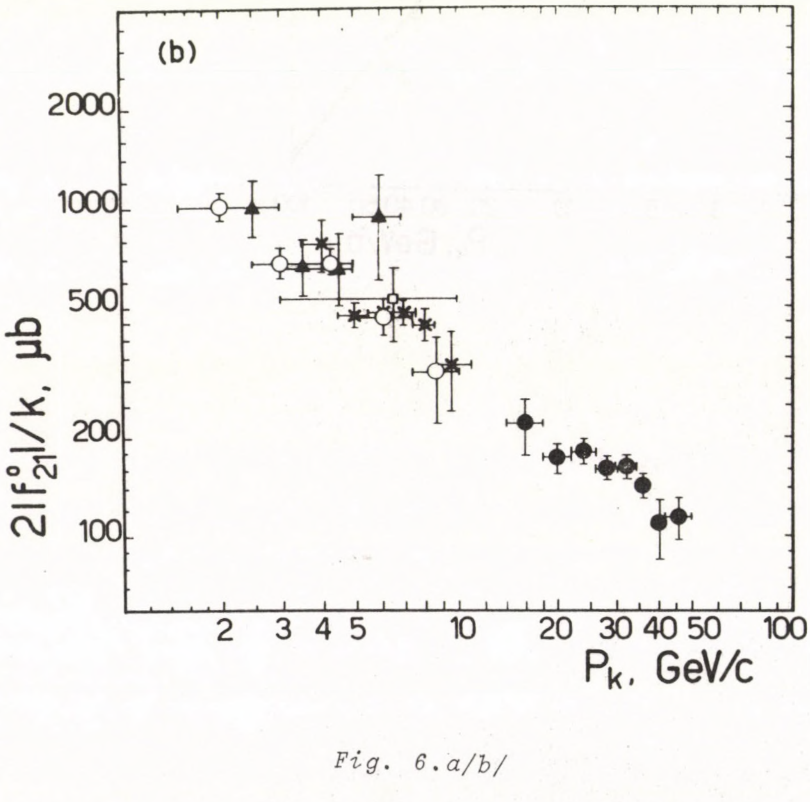

(b)
$2|f_{21}^{o}|/k$, μb
2000
1000
500
200
100
2
3
4
5
10
20
30
40
50
100
P_K, GeV/c

Fig. 6.a/b/

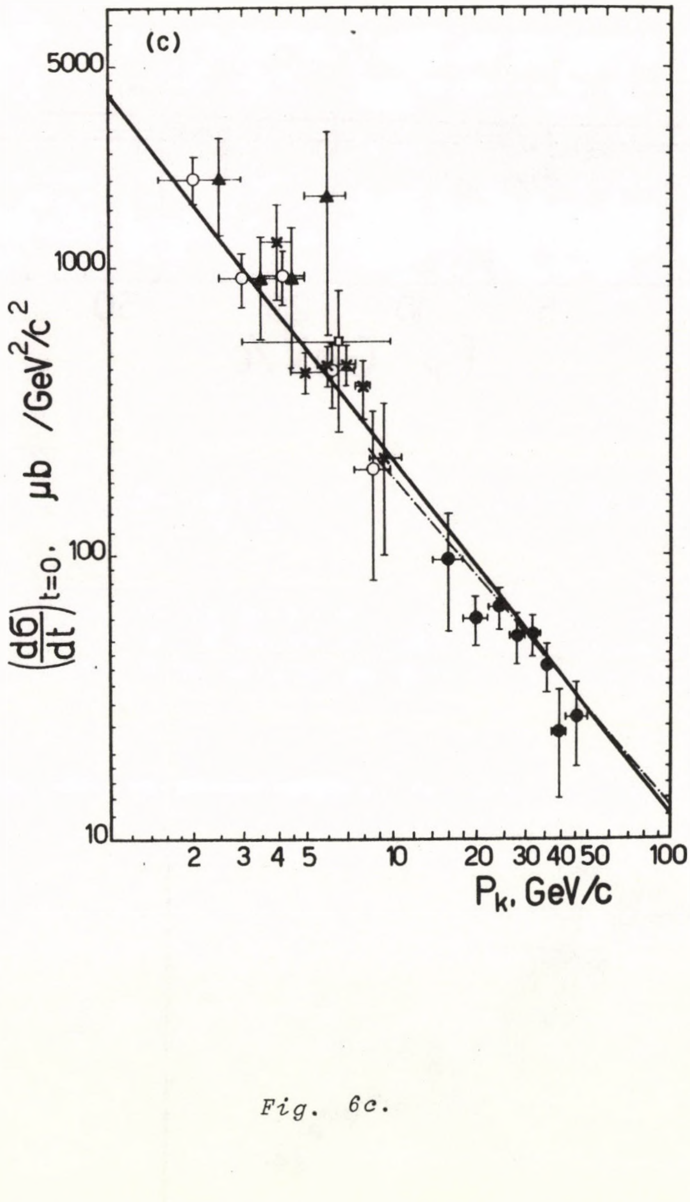

(c)
5000
1000
100
10
2
3
4
5
10
20
30
40
50
100
P_k, GeV/c
(dσ/dt)_{t=0}, μb /GeV²/c²

Fig. 6c.

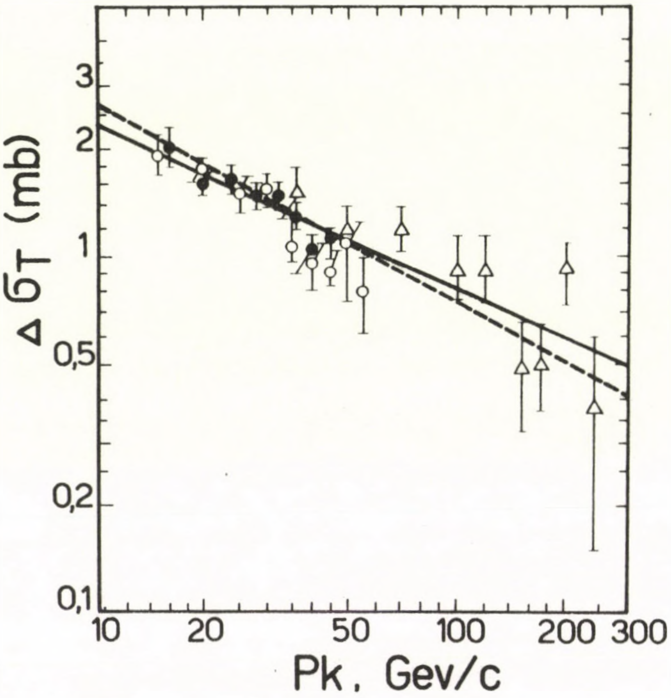


Fig. 7.

ERRATUM

Page 12 last paragraph should be read:

The decrease of $\Delta\sigma(p)$ in the momentum range 10-50 GeV/c observed in this experiment and the energy independence of the K^-n total cross section[14/] in the same energy interval constitute the rise of the K^+n total cross section which was independently observed in direct measurements[16/].

Kiadja a Központi Fizikai Kutató Intézet
Felelős kiadó: Jéki László, a KFKI Részecske- és Magfizikai Tudományos Tanácsának elnökhelyettese
Szakmai lektor: Pintér György
Nyelvi lektor: Kluge Gyula
Példányszám: 455 Törzsszám: 76-252
Készült a KFKI sokszorositó üzemében
Budapest, 1976. április hó