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NEUTRAL KAON REGENERATION ON CARBON IN THE MOMENTUM REGION OF 16 - 40 GEV/C

Dubna - Berlin - Budapest - Prague - Serpukhov - Sofia Collaboration

1973

ЛАБОРАТОРИЯ ВЫСОКИХ ЭНЕРГИЙ

Альбрехт К.-Ф., Бирулев В.К., Деак Ф., и др. **E1 - 7353**

Регенерация нейтральных каонов на углероде в области импульсов 16-40 Гэв/с

(II Международная конференция по элементарным частицам, Экс-он-Прованс, Франция, 6 - 12 сентября 1973 г.)

Измерена амплитуда регенерации нейтральных каонов на углероде. Модуль и фаза амплитуды согласуются с расчетами по оптической модели ядра.

Препринт Объединенного института ядерных исследований.
Дубна, 1973

Albrecht K.-F., Birulev V.K., Deak F. et al. **E1 - 7353**

Neutral Kaon Regeneration on Carbon in the Momentum Region of 16 - 40 GeV/c

(II International Conference on Elementary Particles, France, 6 - 12 September, 1973)

The absolute value and the phase of the regeneration amplitude $K^\circ_L - K^\circ_S$ on carbon have been measured. In the momentum range 16-40 GeV/c the phase is constant within the limits of experimental errors and coincides with the regeneration phase on hydrogen. Both the absolute value and the phase of the regeneration amplitude on carbon are in agreement with optical model calculations.

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The investigation of the energy dependence of the neutral kaon regeneration on different materials has been proposed in 1967 [1, 2]. Since the phenomenon of regeneration is due to the fact that K^o and $\bar{K}^o$ interact with matter in a different way[3, 4], the investigation of the transmission regeneration on hydrogen and deuterium can give an important information on the energy dependence of the K^op and K^on scattering amplitudes and, in particular, it enables one to check the validity of the Pomeranchuk theorem [5]. On the other hand, studying the transmission and diffraction regeneration on complex nuclei one can estimate the electromagnetic size of neutral kaons.[20]

A part of this experimental program has been completed at the 70 GeV/c Serpukhov accelerator during 1970-1972 in a series of measurements of the regeneration on hydrogen [6, 7], deuterium and carbon in the momentum range of 14 - 50 GeV/c. Here we report the preliminary results of the measurements of the $K^o_L - K^o_S$ regeneration in the 1 m carbon regenerator.

The measurements have been performed with the help of an on-line spectrometer [8] detecting $\pi^+\pi^-$ decays of incident K^o_L- and regenerated K^o_S-mesons. The intensity of the $\pi^+\pi^-$ decays of K_L-and K_S-mesons behind a block of matter placed in the K^o_L beam is described by a very well-known formula :

$$I(p,t) \propto \varepsilon(p,t)\Big[|\rho(p)|^2 e^{-t/\tau_S} + |\eta_{+-}|^2 e^{-t/\tau_L} + 2|\eta_{+-}||\rho(p)|\, e^{-t/2\,[1/\tau_S + 1/\tau_L]} \cos(\Delta m t + \phi_\rho(p) - \phi_{+-})\Big], \tag{1}$$

where t is the decay time determined in the kaon rest frame from the downstream edge of the regenerator ($t = m_K z/pc$, m_K and p are the kaon mass and momentum, respectively);

$\varrho(p) = |\varrho(p)| e^{i\phi_\varrho(p)}$ is the coefficient of the transmission regeneration;

$\eta_{+-} = |\eta_{+-}| e^{i\phi_{+-}}$ is the ratio of the decay amplitudes : $A(K_L^0 \to \pi^+\pi^-) / A(K_S^0 \to \pi^+\pi^-)$;

$\Delta m = (m_L - m_S)\hbar^{-1}$; m_L, m_S, τ_L and τ_S are the mass difference, masses and mean lifetimes of long- and short-lived kaons and $\mathcal{E}(p, t)$ is the detection efficiency determined by the Monte-Carlo method.

The regeneration coefficient can be expressed as a product of three terms : number of nuclei per unit of the volume N, difference of K^0N and $\bar{K}^0N$ forward scattering amplitudes $f_{21}^0 \equiv 1/2\left[f^0(p) - \bar{f}^0(p)\right]$ (regeneration amplitude) and a term related to the regenerator length ℓ :

$$\varrho(p) = \frac{\pi N \cdot c}{m_k} i\left(f^0(p) - \bar{f}^0(p)\right) \frac{1 - \exp\left[(i\Delta m - \frac{1}{2\tau_s})\ell m_k/pc\right]}{-(i\Delta m - \frac{1}{2\tau_s})} \quad (2)$$

For a very thin regenerator the phase of regeneration coefficient coincides with that of regeneration amplitude :

$$\phi_\varrho^{\ell \to 0}(p) = \phi_f(p) = \arg i\left(f^0(p) - \bar{f}^0(p)\right) \quad (3)$$

In general,

$$\phi_\varrho(p) = \phi_f(p) + \arg \frac{1 - \exp\left[(i\Delta m - \frac{1}{2\tau_s})\ell m_K/pc\right]}{-(i\Delta m - \frac{1}{2\tau_s})} = \phi_f(p) + \phi_{\Delta m}(p) \quad (4)$$

The experimental setup was the same as in our previous experiments /6, 7/ (Fig. 1). The magnetic spectrometer /8/ consists of multiwire spark chambers with magnetostrictive readout. The triggering signal is provided by scintillation counter logics ($\bar{A}$, FI, FII, GI, GII, $\bar{A}_L$, $\bar{A}_R$). A shower detector and an iron range telescope serve to separate pions from the electrons and muons produced in the semi-leptonic decay modes of K_L^0.

The charged particle pairs of the decaying K-mesons were recorded in the 9 m decay zone and the crossing geometry behind the analysing magnet was required. Our result is based on approximately 2×10^5 triggers. After the geometrical reconstruction /9/ we were left with 90385 events.

Several standard cuts were introduced to enrich the two-pion decay content of the sample relative to the three-body decays and the neutron induced interactions in the decay volume. The most important cuts the events have undergone were : $|m_K - m_{\pi\pi}| \leq 30$ MeV/c^2 and $\theta^2 \leq 6 \times 10^{-6}$ rad^2, where $m_{\pi\pi}$ is the invariant mass of the charged particle pair under the assumption that they are both pions and θ is the angle between the vector sum of the momenta of the two decay particles and the known K_L^0 direction. This procedure reduced our sample to 11969 events.

After studying in detail the x - y profiles at different z planes as well as other distributions of physical importance and comparing them with the corresponding Monte-Carlo distributions, fiducial cuts were applied to the decay vertex and to the charged particle trajectories in the wire chambers, magnet gap and trigger counters. At the same time the electron or muon signatures were also determined for the true $K_{\mu 3}$ and K_{e3} events.

All events surviving the fiducial cuts and a more restricted mass criterion (485 MeV/$c^2 \leq m_\pi \leq$ 510 MeV/c^2) with appropriate μ or e flags were recorded on a final DST.

The $m_{\pi\pi}$ distribution of the retained 4311 events with the double pion signature is shown in Fig. 2. The large peak centered at the kaon mass comes from the $K^0 \to \pi^+ \pi^-$ decays seen over a small and approximately constant background from unidentified decays or interactions. The θ^2 angular distribution for the same events (Fig. 3) exhibits a sharp transmission regeneration peak in comparison with that of "vacuum" regeneration. It is remarkable that the background θ^2 distributions in these two cases are very similar and can be approximated with a linear expression.

Although the transmission regeneration is the overwhelmingly dominating $K^0 \to \pi^+ \pi^-$ decay source, the diffraction regeneration can also be observed. In Fig. 4 the invariant mass distribution is shown with and without a carbon regenerator for the angular range of 0.8-6 mrad^2 where the transmission regeneration practically does not contribute. The enhancement in the region of the kaon mass clearly shows the diffraction regeneration on carbon.

The remaining background under the transmission regeneration peak for the events from the DST divided into proper time and momentum bins of 0.5 x 10^{-10} sec and 4 GeV/c width, correspondingly, has been determined by a linear extrapolation of the angular distribution in the angular variable θ^2 fitted to an expression of the form :

$$N(t,p) \propto \frac{1}{\theta_0^2(p)} \cdot e^{-\frac{\theta^2}{\theta_0^2(p)}} + A(t,p) + B(p)\ \theta^2 \ . \qquad (5)$$

Here the first term represents the transmission regeneration peak broadened to a finite θ_0 (p) due to the finite angular resolution of the detector, and the remaining terms represent the background contamination.

The further analysis has been performed as follows. Let us denote by q_i the probability of the i-th event to be observed with certain values of t_i, θ_i, $m_{\pi\pi\ i}$ and p_i. The probability q_i depends on these quantities as well as on $\phi = \phi_{+-} - \phi_{if}$ and $r = |\rho(p)/\eta_{+-}|$ through eqs. (1) and (4).

In order to deduce r and ϕ, the goal of this experiment, we applied the maximum likelihood method, where we used the product of the probabilities q_i as a likelihood function. In other words, instead of dividing our sample of N events into proper time and θ^2 bins we were looking for the maximum of

$$L = \prod_{i=1}^{N} q_i$$

as a function of r (p) and ϕ (p). Although this latter method is more difficult to apply, the assignment of each event with its own probability of observation uses the maximum information available. Therefore this method is expected to result in less statistical errors than the classical one where the events are grouped in finite intervals. Moreover, by means of this method we were able to derive a momentum-independent phase, ϕ, without any use of the kaon momentum spectrum.

We have performed the number of fits with a various set of parameters assuming that r_j is constant ($j = 1, \ldots, 6$) in the j-th momentum bin at $\Delta p = 4$ GeV/c in size. The results are summarized in Table I. The fits for two and three momentum bins show that a constant phase assumption is a reasonable one in accordance with the optical model calculation that predicts only a slight variation of the phase in the momentum range of 16-40 GeV/c. In these fits we used $\tau_s = 0.8958 \times 10^{-10}$ sec /10/ and $\Delta m = 0.542 \times 10^{10}$ sec^{-1} /11/.

We have also performed the fit assuming that the phase is independent of momentum for the region of 16-40 GeV/c. In this case we had a 7 parameter fit (ϕ and r_j, $j = 1, \ldots, 6$). In Fig. 5 the corresponding likelihood contours can be seen at values $\exp(-1/2\, n^2) \times L_{max}$ ($n = 0, 1, \ldots$) as a function of K_ϕ and M_r, the likelihood function being taken at $\phi = \phi^{fit} + K_\phi \delta\phi^{fit}$ and $r_i = r_i^{fit} + M_r \cdot \delta r_i^{fit}$.

The final results are given in Table II with $|\eta_{+-}| = 0.00232$ that is the value of ref. /12/ corrected for τ_s of ref. /10/ used by us. The common phase is expressed by a Δm and τ_s dependent form as follows :

$$\phi = \phi_{+-} - \phi_{if}\,(16 \leq p \leq 40 \text{ GeV/c}) = 82.6^0 \pm 16.2^0 + 128^0 \times \frac{\Delta m - 0.542 \cdot 10^{10}\ \text{sec}^{-1}}{0.542 \cdot 10^{10}\ \text{sec}^{-1}} - 53.6^0 \times \frac{\tau_s - 0.8958 \cdot 10^{-10}\ \text{sec}}{0.8958 \cdot 10^{-10}\ \text{sec}}.$$

Note that in our fitting procedure ϕ is independent of the chosen value of $|\eta_{+-}|$. Taking the central value of ϕ and the known value of $\phi_{+-} = 43 \pm 3^0$ /16/, we obtain for this region the phase of the carbon regeneration amplitude $\arg(f^0(p) - \bar{f}^0(p)) = -129^0 \pm 16^0$

In Fig. 6 $2 \cdot |f_{21}|/k = |f - \bar{f}|/k$ is shown together with the results of earlier measurements for K_L^0- and $K^\pm$-mesons /17-19/ and the optical model calculations.

We have determined the same parameters also by means of the classical method with the kaon momentum spectrum obtained in our previous experiment /6,7/. The two methods are in reasonable agreement.

The optical model calculations used as input data the total cross sections $\sigma_t(K^0p)$, $\sigma_t(K^0n)$, $\sigma_t(\bar{K}^0p)$, $\sigma_t(\bar{K}^0n)$ and the phases of the corresponding forward elastic scattering amplitudes. These input data were taken from ref. /13/, where they were calculated as the best fit to the existing experimental results in Regge-parametrization taking into account the cuts and assuming the Pomeranchuk model to be valid. In our calculations we used for carbon the same distribution of the nucleon density in nuclei for protons and neutrons. Two density distributions were used : the Saxon-Woods formula with the parameters determined from the photoproduction of ρ^0-mesons on nuclei /14/ and the Fermi distribution with two parameters taken from electron scattering experiments. Both the distributions gave similar results.

The main conclusions drawn from the results presented here are the following :

1. The phase of the carbon regeneration amplitude is independent of energy for the energy range in question and is equal to $\arg(f^0(p) - \bar{f}^0(p)) = -129^0 \pm 16^0$. This value within experimental errors coincides with the phase of the hydrogen regeneration amplitude /6,7/.

2. The measured phase and the modulus of the carbon regeneration amplitude are in good agreement with the optical model predictions.

3. The optical model condition of the consistency of the hydrogen and carbon regeneration measurement put forward by Goldberg and Telegdi /15/ has been checked. Although in our case the consistence is fulfilled, we are planning a more decisive test on this subject with improved statistics.

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Table I. Results of fitting of experimental data by the maximum likelihood method in different momentum intervals.

	$r = \lvert \varrho / \eta_{+-} \rvert$	$\phi = \phi_{+-} - \phi_{if}$
FIT-1 16 GeV/c $\le p \le$ 24 GeV/c	r (16 - 20) = 9.41 ± 1.82 r (20 - 24) = 8.59 ± 2.48	ϕ = (16 - 24) = 75.0° ± 19.4°
FIT-2 24 GeV/c $\le p \le$ 32 GeV/c	r (24 - 28) = 10.58 ± 2.97 r (28 - 32) = 8.68 ± 2.33	ϕ = (24 - 32) = 88.5° ± 20.5°
FIT-3 28 GeV/c $\le p \le$ 40 GeV/c	r (28 - 32) = 7.46 ± 2.82 r (32 - 36) = 7.53 ± 3.21 r (36 - 40) = 8.29 ± 4.19	ϕ = (28 - 40) = 76.2° ± 27.8°

Table II. Different physical parameters obtained by fitting experimental data by the maximum likelihood method on the assumption that the regeneration amplitude phase is independent of the momentum of incident K_L^o.

$\langle p \rangle$ [GeV/c]	$\lvert \varrho / \eta_{+-} \rvert$	$\lvert f - \bar{f} \rvert / k$ [mb]	$\Delta\sigma = \frac{4\pi}{k} \, \mathrm{Im} \lvert f - \bar{f} \rvert$ [mb]
18.57	10.05 ± 1.82	2.14 ± 0.39	- 21.2
22.08	9.52 ± 2.38	1.95 ± 0.49	-19.3
25.97	9.83 ± 2.46	1.96 ± 0.49	-19.4
29.85	8.15 ± 2.04	1.58 ± 0.40	-15.7
33.77	8.08 ± 2.46	1.54 ± 0.47	-15.3
37.82	8.93 ± 3.87	1.68 ± 0.72	-16.7

ϕ (16 - 40) = 82.6° ± 16.2°

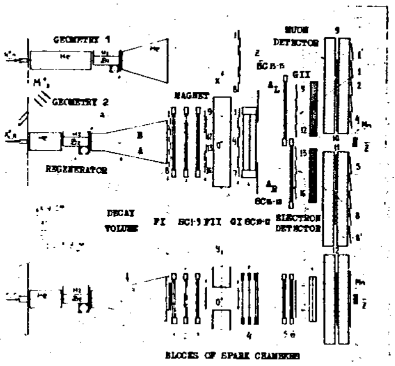

Fig. 1. The layout of the on-line spectrometer.

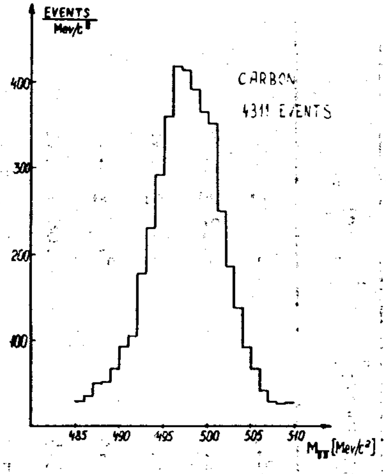

Fig. 2. The invariant mass distribution of the events with $\theta^2 \leq 6$ mrad^2.

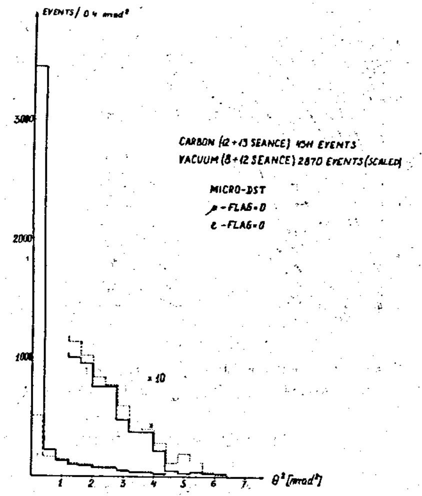

Fig. 3. The angular distribution of the events with the invariant mass $m_{\pi\pi}$ in the region of 485–510 MeV/c^2.

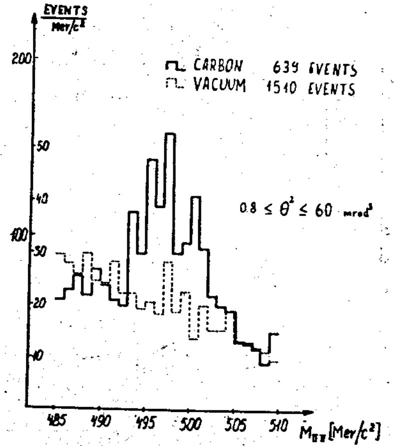

Fig. 4. The invariant mass distribution with and without carbon regenerator for the events taken in the angular range of 0.8–6 mrad^2.

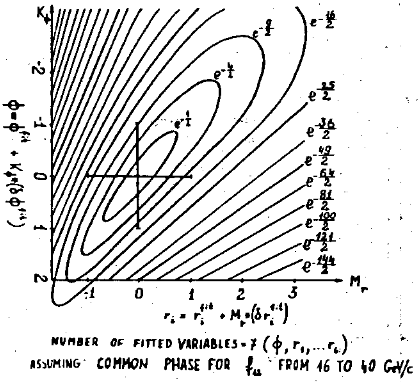

Fig. 5. Likelihood contours at the values

$$L = L_{max} * \exp/-1/2\ n^2/.$$

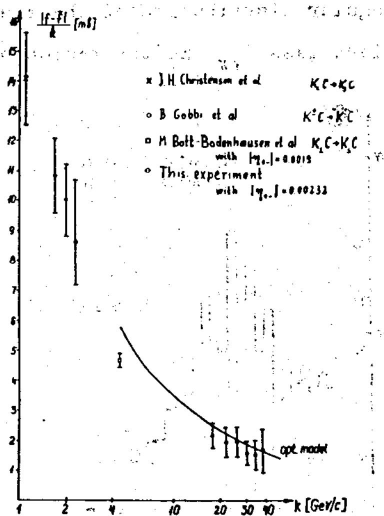

Fig. 6. Experimental results for $|f^0 - \bar{f}^0|/k$ and optical model predictions at high energies.