MEASUREMENT OF π^+ and K^+ LIFETIME AND TOTAL CROSS SECTION OF THE SUBTHRESHOLD K^+ MESON PRODUCTION

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Lifetimes of π^+ and K^+ mesons (τ_{π^+} and τ_{K^+}) are important characteristics of the elementary particles. In spite of the fact that the modern state of theory cannot calculate τ_{π^+} and τ_{K^+} with high accuracy, their values give the chance to define the decay constants f_π and f_K which are very often used in many calculations and can be considered as very important fundamental constants. Precise knowledge of τ_{π^+} and τ_{K^+} is necessary to check the e–μ universality through the ratio of π^+ and K^+ decay rates to $e^+\nu$ or $\mu^+\nu$. Theoretically this ratio is predicted with the accuracy of $5 \cdot 10^{-4}$. Experimentally it is known with much worse precision mainly because of the poor knowledge of τ_{π^+} and τ_{K^+}. And finally, one more problem possibly exists for K^+ mesons: the values of τ_{K^+} measured with two different methods (in flight or at rest) differ by 2–3%.

One of the goals of this work was to measure τ_{π^+} and τ_{K^+} with a new method proposed and developed at PNPI [1–3].

These precise measurements of the lifetimes of π^+ and K^+ mesons were based on:
(a) production of a beam of positive muons (μ^+) from the decay of π^+ mesons stopped in a meson-production target,
(b) utilization of the periodic time microstructure of the proton beam.
This time microstructure of the proton beam extracted from the PNPI synchrocyclotron consists of a train of micro-bunches with a width at half-maximum of 5 ns and a repetition period $T_0 = 75$ ns. The probabilities for the appearance of protons in the time intervals $\Delta t = 40$ ns and 35 ns between micro-bunches did not exceed $5 \cdot 10^{-6}$ and 10^{-6}, respectively. The overwhelming majority of the protons, which reach the target, produce π^+ or K^+ mesons during the proton micro-bunches. Immediately after their production, some of the π^+ or K^+ mesons are stopped in the same target. During the time intervals between the micro-bunches these particles undergo an exponential decay to neutrino and μ^+ with momenta of 29.8 MeV/c (π^+ decay) or 236 MeV/c (K^+ decay). The μ^+ mesons which escape from the interior of the target lose part of their energy due to ionization losses resulting in a momentum spread. Under the conditions of these experiments, this spread was 0–29.8 MeV/c or 215–236 MeV/c. Some of the μ^+ mesons fly off at the angle of $60° \pm 5°$ relatively to the direction of the proton beam and are selected by a magnetic spectrometer consisting of two magnets and seven quadrupole lenses, with a momentum resolution of 5% [3]. The central momentum to which the spectrometer is tuned is 28.5 MeV/c or 230 MeV/c. This spectrometer also captures some background μ^+ mesons from the decay of π^+ mesons emitted from the target towards the spectrometer and decayed in the front part of the latter. However, nearly all the background mesons are produced in the interval of 5 ns after the proton interaction with the target, so they do not appear inside the time interval Δt used for the lifetime measurements.

The target was in the vacuum chamber of the spectrometer. The detector was placed 8 m downstream of the target behind a thin exit window (consisting of 0.1 mm Mylar-like material). The detector of the μ^+ mesons with the momentum of 230 MeV/c consisted of scintillation counters and it was described in Ref. [2]. Detection [3] of the μ^+ mesons with the momentum

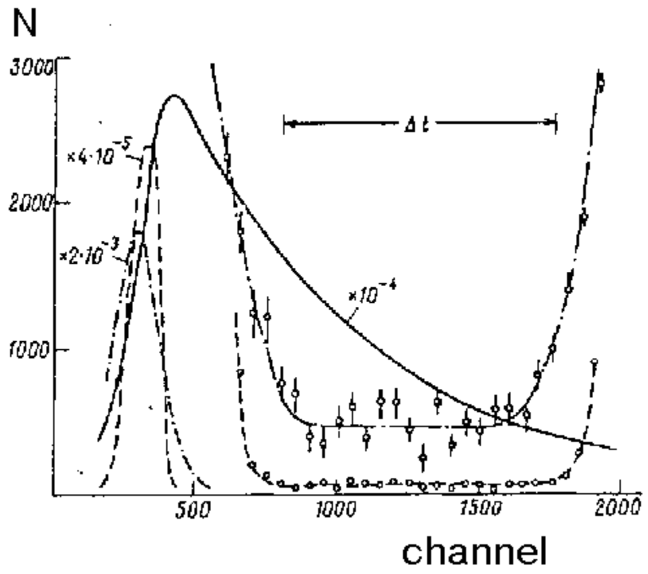

Fig. 1. Time distributions of μ^+ mesons with the momentum of 28.5 MeV/c (—), of π^- mesons with the momentum of 600 MeV/c (∘ ∘ ∘; – – –), of background muons with the momentum of 28.5 MeV/c (∘ ∘ ∘; – · – · –). The solid curve and the narrow peaks shown by the dashed and dot–dashed curves are drawn through the experimental points (the latter are not shown) after multiplication by the factors of 10^{-4}, $4{\cdot}10^{-5}$, and $2{\cdot}10^{-3}$, respectively. A summation was carried out over 50 channels, the original designations of the channels of the time-interval meters having been retained. One thousand channels of the time-interval meter correspond to 39.1764±0.0008 ns.

of 28.5 MeV/c was performed with plastic scintillator counters 65 mm in diameter and 0.1 mm thick and with two plastic scintillator anticoincidence counters 65 mm in diameter and 0.3 mm thick. Using the $\Delta E/\Delta x$ criterion and a fast selection logic (the dead time was 15 ns) resulted in a low detection efficiency ($< 10^{-8}$) for positrons and π^+ mesons captured by the magnetic spectrometer, while the positive muons were detected with the efficiency approaching 100%. The average number of μ^+ mesons detected during the interval T_0 did not exceed $8 \cdot 10^{-4}$.

The signals from the detector went to a time-interval meter if they were not preceded or followed (in the time intervals $\pm T_0$) by other signals. The average value of a channel of the time-interval meter ($(391764 \pm 8) \cdot 10^{-7}$ ns/channel) during the time interval $\Delta t = 40$ ns, as well as the integral ($3 \cdot 10^{-4}$) and differential (10^{-3}) nonlinearities of the time-interval meter, were measured during the experiment in the time intervals between cycles of extraction of the proton beam. For these measurements we used pulses from a quartz generator and random signals from a scintillation counter irradiated by electrons from a radioactive ^{90}Sr source.

Using the time-interval meter, we measured time distributions of the positive muons with respect to reference signals tied to a certain phase of the high frequency sine wave of the HF generator of the accelerator. These reference signals determine the moments at which the protons pass through the target (Figs. 1,2).

The time distributions of positive muons from the decays of π^+ or K^+ mesons stopped in the target are similar to the solid curve in Fig. 1. The smoothly descending right-hand slope of this curve can be described over the interval Δt by

$$N(t) = N_0 \exp(-t/\tau),$$

where τ is the lifetime of the π^+ or K^+ mesons. The steep left-hand slope has a transition region duration of which is determined by the length of the proton micro-bunch and by the solid angle, momentum resolution, and length of the spectrometer. In this transition region the π^+ or K^+ mesons stopped in the target are accumulated, and the background muons are produced (the narrow dot-dashed peak in Fig. 1).

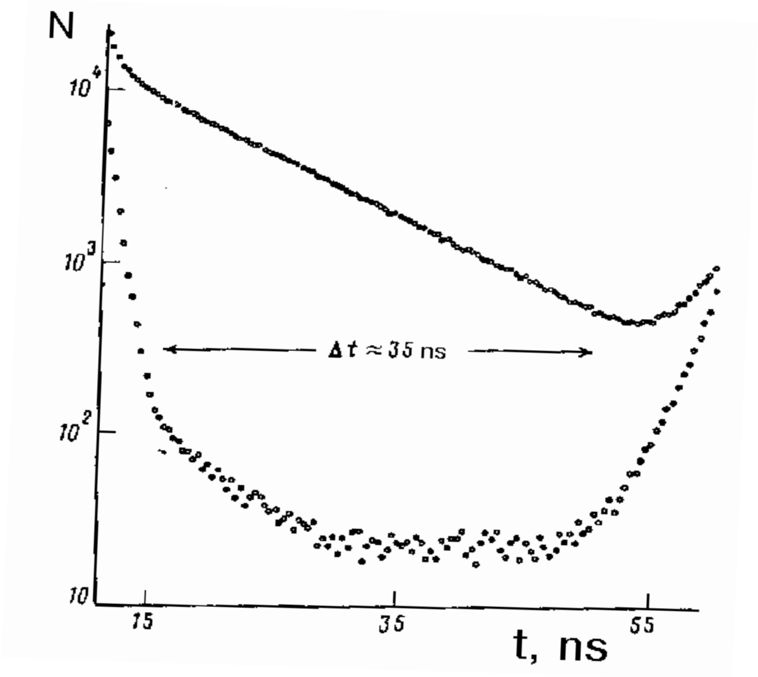

Fig. 2. Part of the time distribution (inside the transition region) of positive muons with the momentum of 230 MeV/c (upper curve) and total background spectrum of the muons with the momenta of 210 and 260 MeV/c.

To determine the interval Δt during which the contribution from background processes is minimal, we carried out some background measurements for μ^+ mesons with momenta of 210 and 260 MeV/c (K^+ decay) and for μ^+ and μ^- mesons with momenta of 28.5 MeV/c (π decay). For the μ^+ mesons with the momentum of 28.5 MeV/c the background distribution was measured after a Mylar filter 0.4 mm thick. This filter was inside the vacuum chamber of the spectrometer at the distance of 20 cm from the target. It absorbed all the positive muons from decay of π^+ mesons stopped in the target. After the small fraction of positive muons from the decay of π^+ mesons stopped in the filter was subtracted, we obtained the time distribution of the background positive muons identical to the time distribution of negative muons with the momentum of 28.5 MeV/c measured in the absence of the filter after the polarity reversal of all the magnetic elements of the spectrometer. To monitor the proton beam (that is necessary to subtract the background spectra) and also to find an upper estimate of the relative intensity of the proton beam in the interval Δt between the micro-bunches, we used π^- mesons with the momentum of 600 MeV/c emitted from the target at the zero degree angle.

The background conditions in these experiments were such that the relative number of the background events during the time interval Δt did not exceed $2 \cdot 10^{-4}$ (in the case of π^+ decay) or $3 \cdot 10^{-3}$ (K^+ decay). The relative systematic error in the measurements caused by the background subtraction is therefore $\delta_f \approx 3 \cdot 10^{-5}$ for the π^+ decay and $2 \cdot 10^{-4}$ for the K^+ decay. The relative error in the experimental results due to the calibration of the time-interval meter, the nonlinearity function of this meter, and the statistical distortions of the original temporal distribution does not exceed $\delta_k \approx 3.5 \cdot 10^{-5}$ [4,5].

We determined τ by the least-squares fit of the time distributions (corrected for the background and nonlinearity) over the interval Δt selected in such a manner that the values of τ for shorter intervals within Δt agreed with each other within the measurement errors. The possible relative systematic error due to the uncertainty in the choice of the working interval Δt was $\delta_{\Delta t} = 6 \cdot 10^{-5}$ (π^+ decay) or $5 \cdot 10^{-4}$ (K^+ decay).

The total relative systematic error

$$\delta_c = \sqrt{\delta_f^2 + \delta_k^2 + \delta_{\Delta t}^2}$$

is $7.5 \cdot 10^{-5}$ for the π^+ decay and $5.5 \cdot 10^{-4}$ for the K^+ decay. This error was added quadratically to the relative statistical error found through the analysis of the spectra corrected for the background and nonlinearity. The latter error was the main error in these experiments. Under these particular experimental conditions, the results obtained without subtraction of the background or without consideration of the nonlinearity function differ from the actual results by no more than one standard deviation.

To eliminate possible systematic errors which we might have not considered, we measured the lifetime of the π^+ meson using copper, carbon, and quartz targets. This changed the background positron flux (by a factor of 10) and that of π^+ mesons (by a factor of 2), as well as the detector counting rate (by a factor of 2). The measurements carried out with different targets resulted in the following values which agree within the errors:

$$\begin{aligned} \tau_{\pi^+}(\mathrm{C}) &= 26.0349 \pm 0.0078 \text{ ns}, \\ \tau_{\pi^+}(\mathrm{Cu}) &= 26.0329 \pm 0.0076 \text{ ns}, \\ \tau_{\pi^+}(\mathrm{SiO_2}) &= 26.0418 \pm 0.0096 \text{ ns}. \end{aligned}$$

The resulting spectrum from all the three targets contains $1.5 \cdot 10^8$ events in $\Delta t = 38$ ns. The lifetime of the π^+ mesons found from the analysis of this spectrum is

$$\tau_{\pi^+} = 26.0361 \pm 0.0052 \text{ ns} \qquad (\chi^2 = 0.97, \quad \text{C.L.} = 0.60).$$

The accuracy here is four times better than in the world's average result [6].

The lifetime of the K^+ mesons was measured for copper and uranium targets. The numbers of events in the time interval $\Delta t = 35$ ns were $1.5 \cdot 10^5$ and $2.5 \cdot 10^5$, respectively. We found

$$\begin{aligned} \tau_{K^+}(\mathrm{Cu}) &= 12.368 \pm 0.041 \text{ ns} \quad (\chi^2 = 1.06, \quad \text{C.L.}= 0.66) \quad \text{and} \\ \tau_{K^+}(\mathrm{U}) &= 12.451 \pm 0.030 \text{ ns} \quad (\chi^2 = 1.07, \quad \text{C.L.}= 0.63). \end{aligned}$$

These values differ from each other by two standard deviations. The average weighted value is

$$\tau_{K^+} = 12.415 \pm 0.024 \text{ ns}.$$

This result supports the value found previously for the K^+ lifetime by the "at rest" method [6].

The accuracy of the measurements of the π^+ lifetime could be improved by using the considered in this work method at meson factories.

The above described method of identification of the π^+ or K^+ mesons produced and stopped in the same target helped to perform the pioneering measurement of the total cross sections of K^+ meson production in proton-nucleus interactions at 800–1000 MeV. Since low energy kaons are mostly produced in the above energy range, one can use quite small meson-production targets in order to stop in them not less than 95% of all the kaons without serious distortion of the muon spectrum from the decay of kaons stopped in the target. The momentum spectra of these muons are shown in Fig. 3.

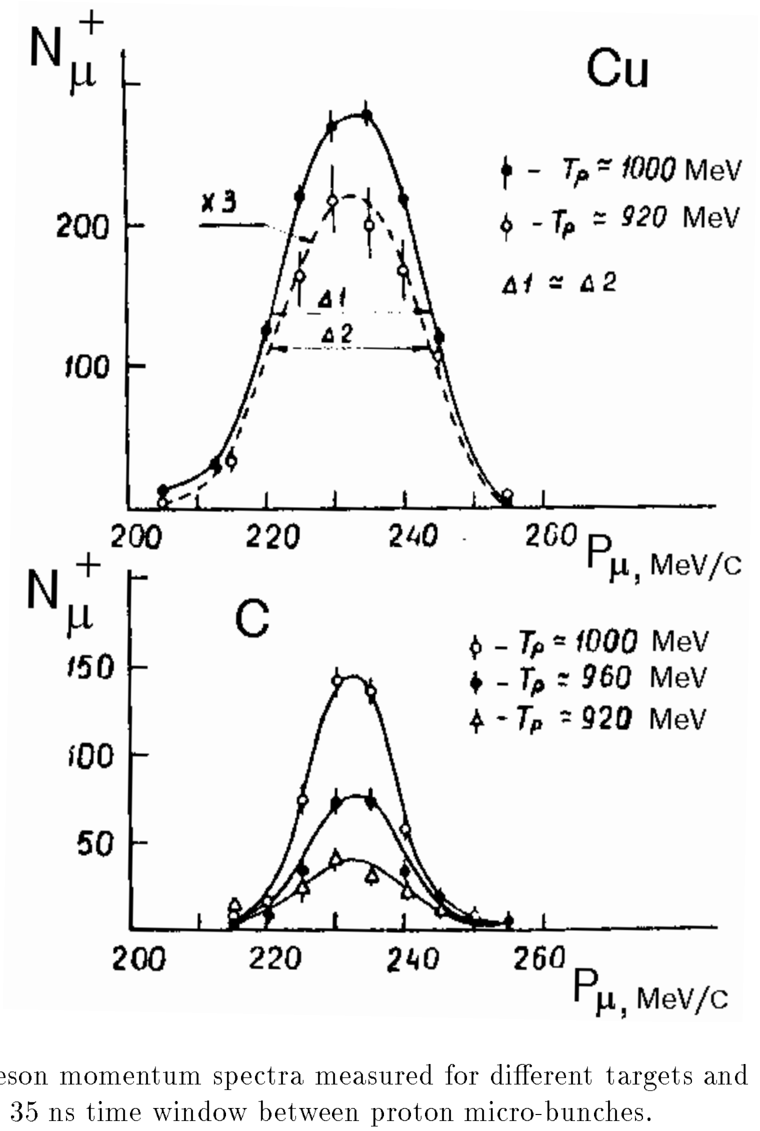

Fig. 3. μ^+ meson momentum spectra measured for different targets and various proton energies in the 35 ns time window between proton micro-bunches.

The absolute values of the total cross sections were obtained by the normalization to the cross sections of production of π^+ mesons [7] escaping the same target into the solid angle of the same magnetic spectrometer simultaneously with the muons registered by the same detector.

It was shown that pions from $pp \to \pi^+ pn$ reaction are perfectly described by the conventional one-pion exchange model (OPEM) if few percents of π^+ mesons from $pp \to \pi^+\pi^- pp$ reaction at low pion momenta are taken into account and the final state nucleon-nucleon interaction (FSI) is included at the momentum region close to $pp \to \pi^+ d$ reaction. Measured double differential cross section for $\pi^\pm$ meson production in pA $\to \pi^\pm$... reactions is satisfactorily described by a simple cascade model [7].

The main goal of the K^+ production study was to investigate the so-called cumulative phenomena, i.e. the processes occurred at small distances during short nuclear time intervals. The data presented in Table 1 were obtained at the proton energies much lower than the threshold of K^+ production in nucleon-nucleon interactions (1.58 GeV) and gave a chance to achieve the record level of cumulativity in the "subthreshold" processes. If it is supposed that kaons are produced only in direct (single-step) reactions, then for the energy interval 800–1000 MeV of the projectile proton one needs a nuclear nucleon moving with the momentum not less than 300–600 MeV/c. If kaons are produced in interactions of the projectile protons with a group of strongly correlated nuclear nucleons (quark bags), than the mass of these correlations must be not less than 3–6 nucleon masses.

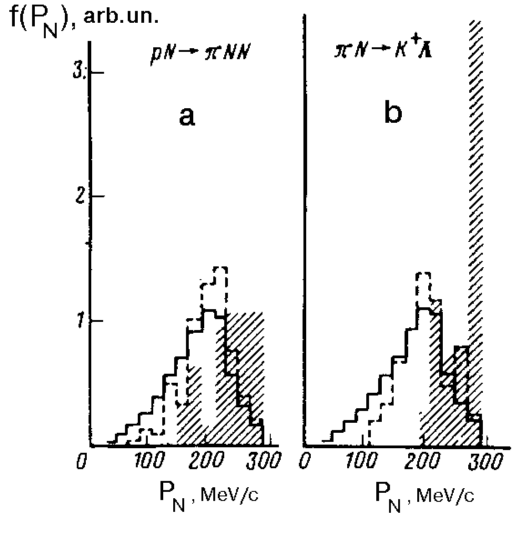

Fig. 4. Momentum distribution of nucleons in nucleus: solid histograms – Tomas-Fermi model; dashed ones – for nucleons participating in the reaction at the incident proton energy of 1000 MeV; shaded ones – for the proton energies of 830–850 MeV.

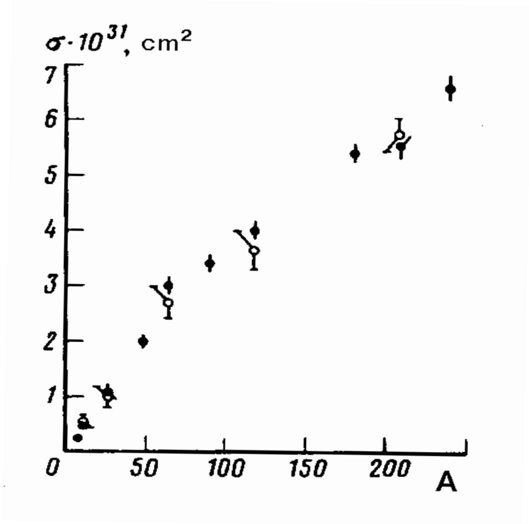

Fig. 5. Dependence of the total cross sections of K^+ mesons production on the atomic number of the target: • – experimental points at the proton energy 995 MeV; ∘ – results of calculations.

Table 1

Total cross section for $pA \to K^+ \ldots$

A	T_p, MeV	$\sigma \cdot 10^{33}$, cm^2	A	T_p, MeV	$\sigma \cdot 10^{33}$, cm^2
	990	21.0 ± 1.0		990	39.0 ± 2.0
	975	15.7 ± 1.2		975	24.9 ± 1.1
	960	9.2 ± 1.1		960	18.5 ± 2.1
	947	8.4 ± 0.8		947	16.2 ± 1.9
	935	7.0 ± 0.8		935	10.9 ± 1.2
	929	4.6 ± 0.4		929	10.5 ± 0.7
	918	3.9 ± 0.4		918	7.8 ± 0.8
Be	907	2.7 ± 0.4	C	912	5.5 ± 0.8
	905	2.8 ± 0.4		905	6.0 ± 0.5
	900	2.2 ± 0.4		900	4.9 ± 0.4
	892	2.34± 0.45		885	3.7 ± 0.1
	878	1.47± 0.28		870	1.8 ± 0.3
	864	0.43± 0.28		842	1.1 ± 0.3
	842	0.82± 0.41			
	835	0.25± 0.21			
	988	298 ± 15		988	550 ± 18
	973	201 ± 14		979	491 ± 21
	959	141 ± 15		973	443 ± 30
	945	119 ± 12		973	396 ± 26
Cu	927	81 ± 5		960	328 ± 25
	916	48 ± 6		959	323 ± 14
	903	48 ± 4		946	220 ± 20
	898	46 ± 3		945	248 ± 13
	853	12 ± 2		933	156 ± 18
	840	8.1 ± 0.9		932	150 ± 14
				927	151 ± 9
	988	405 ± 22		918	97 ± 10
	979	340 ± 12	Pb	916	112 ± 21
	973	335 ± 16		910	77 ± 11
	959	231 ± 21		905	81.4± 4.9
	945	170 ± 11		903	77 ± 6
Sn	927	108 ± 13		898	63 ± 5
	916	86 ± 14		890	38.1± 3.1
	910	75 ± 7		883	28.0± 5.1
	903	50 ± 9		876	24.8± 2.3
	898	49 ± 4		868	28.0± 6.0
	883	24 ± 3		861	15.7± 1.5
	868	24 ± 5		847	10.8± 2.6
	840	8.1± 2.4		840	10.0± 3.0
				833	6.7± 1.2
				804	2.3± 1.2

The comparison of the experimental data on the "subthreshold" production with the results of calculations based on theoretical models considering only direct processes showed that, in the best case, calculations could describe the energy dependence of the total cross sections. The absolute values of the calculated cross sections were 10–100 times less than the experimental data. To understand a mechanism of the "subthreshold" kaon production, the two-step process was also considered. In the first step of this process, intermediate pions are produced in the reactions $pN \to \pi NN$ and $pN \to \pi d$. Then the K^+ mesons are produced in the second step in the reaction $\pi N \to K^+\Lambda$. The two-particle reaction with the deuteron production should give not less than 25% of the total cross sections for the kaon production. When this two-step mechanism (see Fig. 4) was included into the simple cascade model considering nuclei as a normal Fermi-gas [2,8], the calculation proved to be in good agreement with the experimental data (Fig. 5).

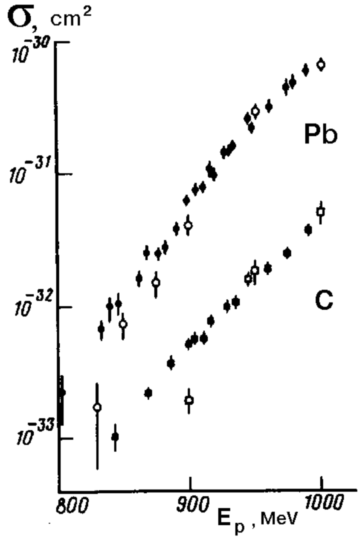

Fig. 6. Dependence of the total cross section of K^+ mesons production on the proton beam energy: • ■ – experiment, ○ □ – calculations.

For the projectile energy in the range from 900 to 1000 MeV (Fig. 6) it is enough to use the Tomas-Fermi momentum distribution with the maximum momentum of the nuclear nucleons less than 300 MeV/c. Below 900 MeV it is necessary to include a high momentum component of the nucleon motion, especially when the second stage ($\pi N \to K\Lambda$) of the two-step process is considered. Recent theoretical calculations (W.Cassing et al., Phys. Lett., 1990. V.B238. P.25) confirmed the dominating role of the two-step mechanism. This mechanism is used now very often for different nuclear reactions, e.g. for η meson production in $pA \to \eta$... reactions. The necessity to include the two-body reaction ($pN \to \pi d$) at the first stage of the two-step process was confirmed by A.A.Sibirtsev and M.Buescher (Z. Phys., 1994. V.A347. P.191). The authors showed that detection of K^+ mesons in correlation with deuterons could be a direct proof of the two-step mechanism. The deuteron from this process would escape the target in the forward direction ($\theta_d \leq 10°$) with the momentum of 850±50 MeV/c, whereas the background deuterons from the secondary pick-up reactions would have more isotropic angular and momentum distributions.

In 1991 the joint Russian–German group proposed a correlation experiment COSY–18 to study the "subthreshold" K^+ meson production in proton-nucleus interaction at the proton energies of 800–1500 MeV of the accelerator COSY at the National Centre KFA (Jülich). In this experiment the direct detection of K^+ mesons will be done. The kaon momentum spectra will be measured both inclusively and in correlation with deuterons and protons with the help of the short-length magnetic spectrometer (shorter than 5 m). All the particles escaping the internal target in the forward direction ($\theta \leq 10°$) will be magnetically deflected from the beam area, detected by telescopes of scintillation and Cherenkov counters and multiwire proportional chambers, and off-line analyzed by space, momentum, energy losses, and time-of-flight criteria. K^+ mesons will be separated from the other particles by a fast trigger. The prototypes of different parts of the spectrometer have been already constructed and tested in meson and proton beams at PNPI, ITEP, and KFA. The experiment is planned to start in 1997.

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