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SUBTHRESHOLD K^+ PRODUCTION IN PROTON-NUCLEUS COLLISIONS

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Initial proton energy dependence of the differential cross sections for subthreshold K^+ production of momentum 1.28 GeV/c at laboratory angle 10.5 degree on Be, Al, Cu and Ta nuclei have been measured. The experiment was carried out in the kinematical region where direct collision of a projectile proton with target nucleon was a dominating kaon production mechanism. The internal nucleon momentum distributions extracted from the data were extended up to 700 MeV/c. Existing models of nucleon spectral functions fail to reproduce the measured energy dependencies.

ПОДПОРОГОВОЕ РОЖДЕНИЕ K^+ МЕЗОНОВ В ПРОТОН-ЯДЕРНЫХ СТОЛКНОВЕНИЯХ

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Измерена энергетическая зависимость дифференциальных сечений подпорогового рождения K^+ мезонов с импульсом 1.28 ГэВ/с под углом 10.5 градусов в лабораторной системе на ядрах Be, Al, Cu и Ta. Эксперимент выполнен в кинематической области доминирования прямого механизма образования каонов в столкновениях налетающих протонов с внутриядерными нуклонами. Получены характеристики импульсных распределений нуклонов в ядрах вплоть до 700 МэВ/с. Данные не удается описать в рамках существующих моделей спектральных функций ядер.

Fig. - 5, ref. - 17 name.

1. INTRODUCTION

The study of hadron production in proton-nucleus collisions below the free nucleon-nucleon threshold is motivated by hopes to learn about the nuclear structure at short internucleon distances as well as the properties of the produced particles in the surrounding nuclear medium. Such investigations can provide an information on the nucleon momentum distributions n($\mathbf{q}$) in wide momentum range. It is accepted that low momentum part of n($\mathbf{q}$) is almost totally dominated by the single particle features of nuclear structure while its high momentum part is governed by short-range properties of nuclear matter. The lack of collision energy in subthreshold processes makes an interpretation of the experimental data less ambiguous because of number of hadron production channels are severely restricted. Within the impulse approximation two channels can contribute to the cross section of K^+ production below the threshold (Fig.1 a,b). First is the process of one-step direct collision of the projectile proton with target nucleon:

$$p + N \to K^+ + Y + N, \qquad (Y = \Lambda, \Sigma), \tag{1}$$

second is a two-step cascade process associated with the production of kaon by intermediate pion:

$$p + N \to N + N + \pi, \qquad \pi + N \to K^+ + Y \tag{2}$$

The high momentum component can be studied only in the direct process because of in the cascade process the internal momenta contribute twice and appears to be rather low. The analysis of the available now experimental data on subthreshold K^+ production in proton-nucleus collisions [1,2,3] evidences for the dominant contribution to the cross section comes from the cascade channel [4-7].

The main goal of the present experiment was to obtain data on subthreshold K^+ production in the kinematical regime where direct mechanism

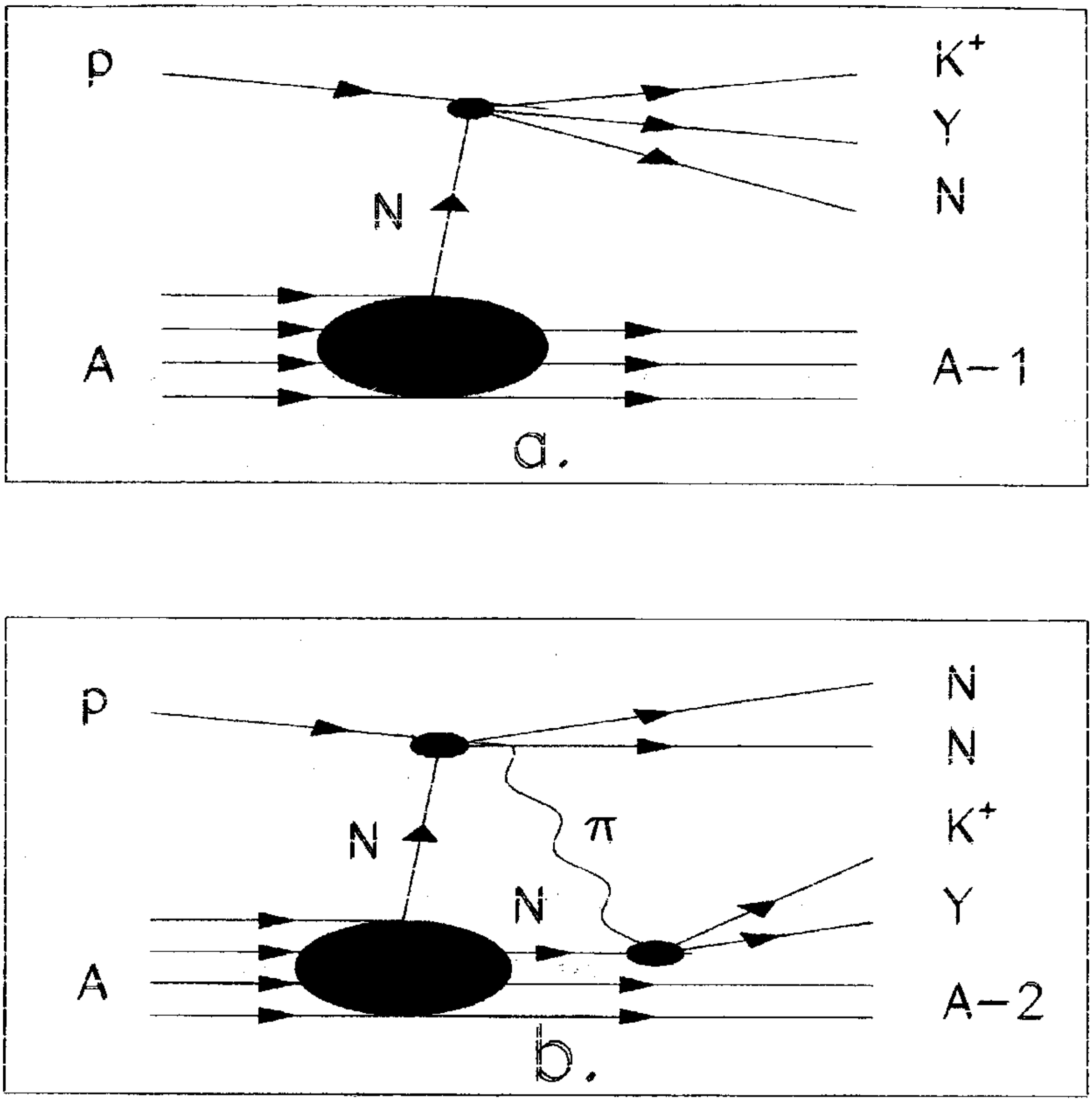

Fig.1. Feynman diagrams for the direct (a) and cascade (b) K^+ production in pA collisions.

significantly prevails over the cascade one. The paper is organized as follows. The choice of the kinematical range is discussed in Sec.2. In Sec.3 the experimental set-up and procedure are described. In Sec.4 the analysis of the obtained data in frame of the folding model for K^+ production via direct channel is presented. The evidences for dominance of direct mechanism in the kinematical conditions of the present experiment are collected in Sec.5. In Sec.6 the internal nucleon momentum distributions extracted from the data are compared to ones obtained from the experiments with electromagnetic probes as well as to the calculation based on the concept of the nucleon spectral function. Finally, the conclusions are presented in Sec.7.

2. CHOICE OF THE KINEMATICS

One-step kaon production process is directly related to the nucleon momentum distribution n(q). Since n($\mathbf{q}$) falls rapidly with nucleon momentum the cross section for the direct channel depends mainly on q_{min} - minimal internal nucleon momentum with which projectile proton should collide to produce kaon of observed kinematical parameters[1]. Therefore the relative contribution of the direct and cascade channels to the cross sections measured in different experiments can be reasonably compared at the same value of q_{min} i.e. at equal strength of the proton induced reaction channel.

The value of the cross section for cascade kaon production depends on three factors. The most important of them is a probability to produce intermediate pion of high enough momentum for subsequent kaon production. Second factor is determined by a probability of pion inelastic interaction inside the same nucleus. Finally, third factor contains the differential cross section for pion induced K^+ production and appears to be practically the same for the kinematics of different experiments because of it depends mostly on the excess energy above the threshold of $\pi + N \rightarrow K^+ + \Lambda + Y$ reaction. First factor describing a pion spectrum is proportional to $(1 - X_F^R)^n$

[1]The values of q_{min} can be easily calculated taking into account the energy-momentum and strangeness conservation in $pN \rightarrow K^+YN$ reaction, $(P+W-P_K)^2 = (M_Y+M_N)^2$. Here M_Y and M_N stand for hyperon and nucleon masses; $P(E_0, \mathbf{P}_0)$, $W(w, \mathbf{q}_{min})$, $P_K(E_K, \mathbf{P}_K)$ are components of the four-momenta for projectile proton, target nucleon and detected kaon, respectively.

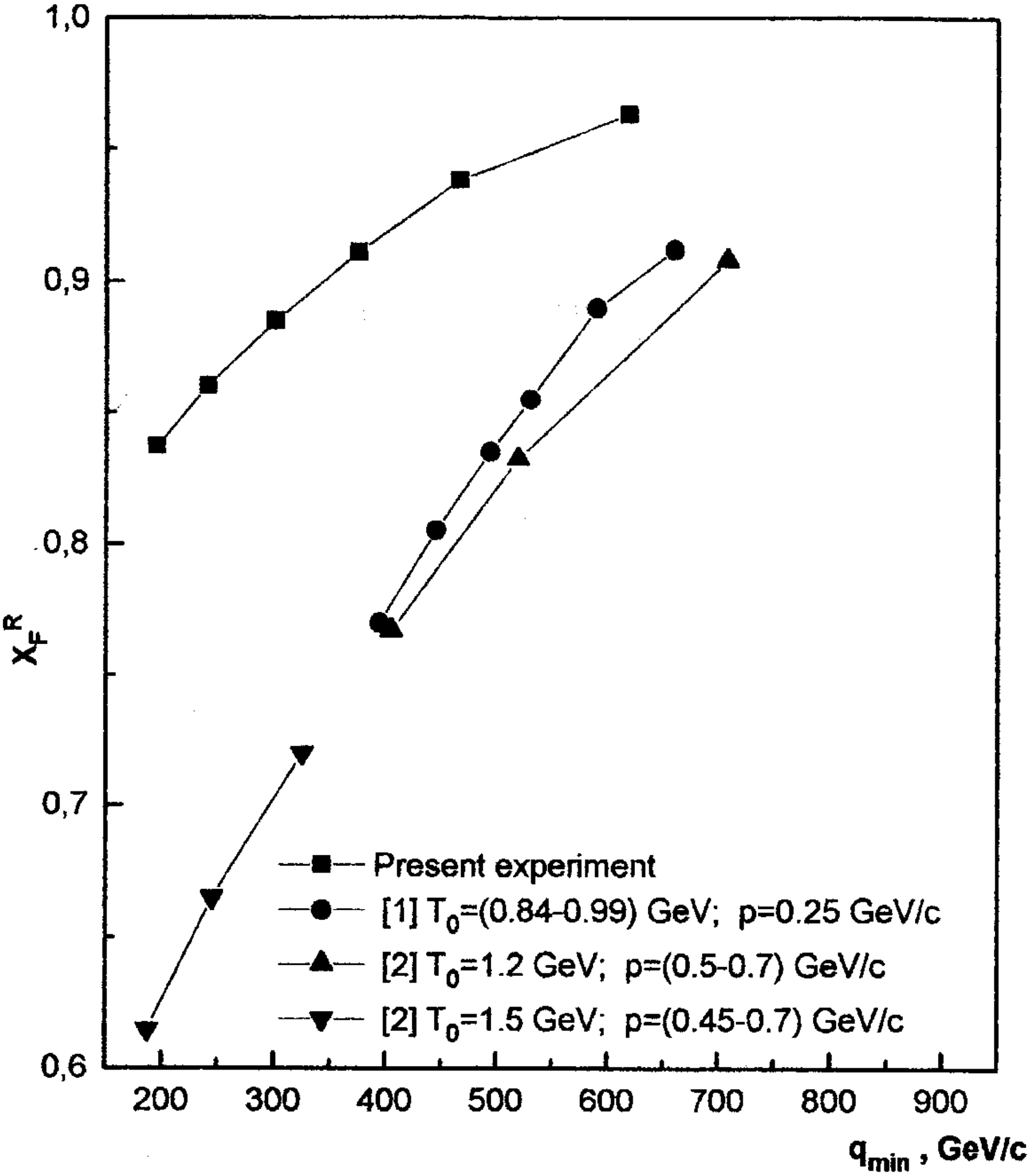

Fig.2. Dependence of X_F^R on q_{min}.

with n>2. Radial Feynman's variable is defined as

$$X_F^R = P/P_{max}, \tag{3}$$

where $P = \sqrt{P_l^2 + P_t^2}$ stands for pion momentum in the proton-nucleus center of mass system, P_{max} is its maximal value. The quantity X_F^R depends on the collision energy, pion momentum and its production angle. It is obvious that the contribution of the two-step channel falls rapidly with increase of X_F^R.

The comparison of minimal X_F^R values for pions which are capable to produce K^+ of detected kinematical parameters in the collision with target nucleon carrying the oppositely directed momentum 0.25 GeV/c as a function of q_{min} is presented in Fig2. Calculations were performed for the kinematical conditions of the available experiments on K^+ production from light nuclei:

- -forward production of low momentum (0.25 GeV/c) kaons by protons in initial energy range 0.84-0.99 GeV [1],
- -production of kaon with momenta 0.45-0.7 GeV/c at 40 deg.(lab) at incident proton energy 1.5 GeV [2],
- -kaon production in the momentum range 0.5-0.7 GeV/c at 40 deg. at 1.2 GeV [2],
- -production of kaon with momentum 1.28 GeV/c at 10.5 deg. in the proton kinetic energy interval 2.0-1.65 GeV (present experiment).

It is seen that at the same conditions for the direct kaon production the contribution of the cascade channel should be significantly suppressed in the kinematics of the present experiment. The pions with momenta up to X_F^R=0.95 which is close to the absolute threshold for their production on the target nucleus are required to produce kaon of detected parameters.

3. EXPERIMENT

The experiment was carried out with internal proton beam of the ITEP synchrotron irradiated Be, Al, Cu and Ta targets less than 100 micron thick. Initial proton energies were determined within the accuracy of 5

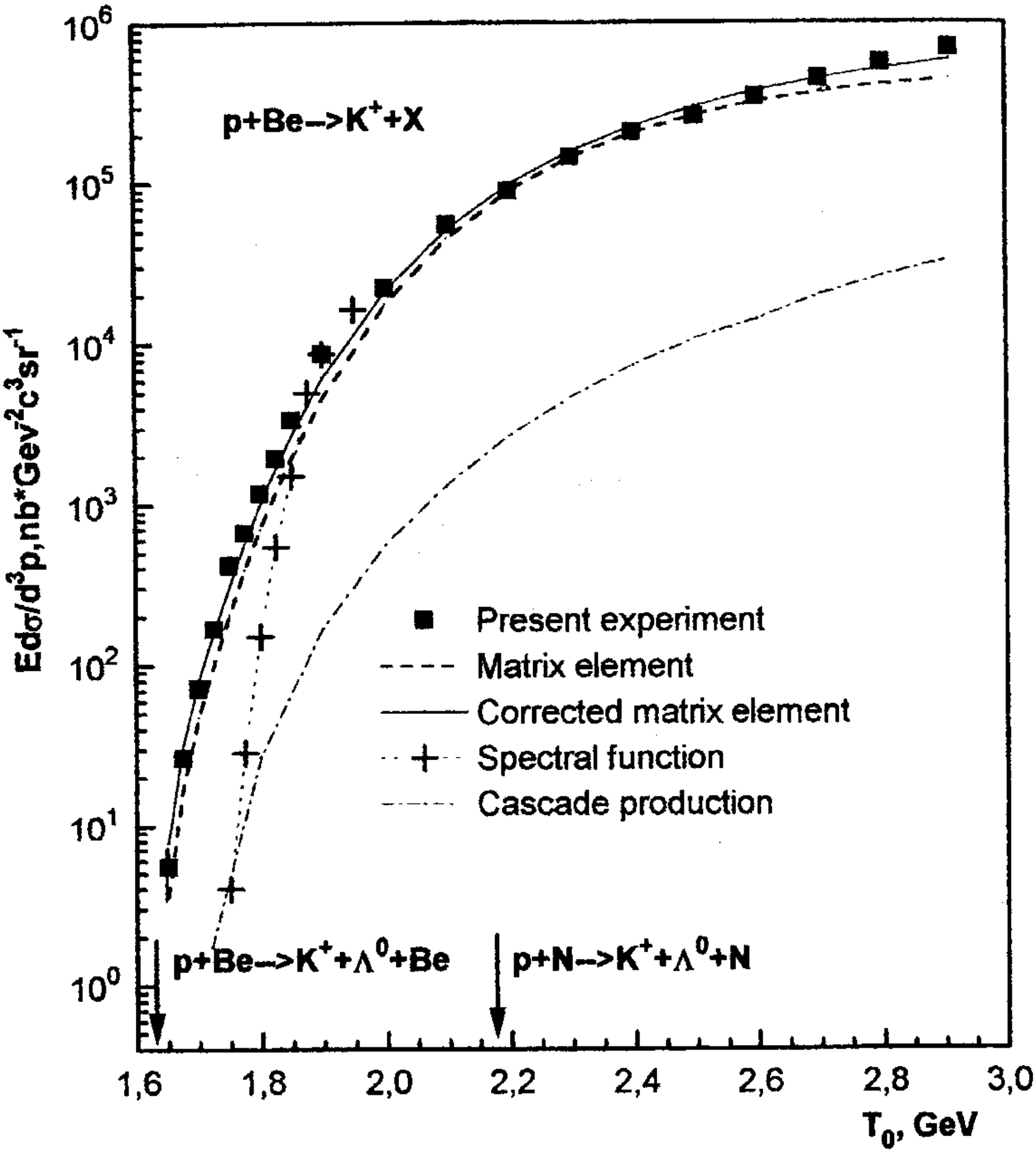

Fig.3. Incident proton energy dependence of the invariant cross section for K^+ production.

MeV by measurements of the accelerating frequency. Secondary particles of momentum (1.28± 0.014) GeV/c were detected at 10.5 degree (lab.) by Focusing Hadron Spectrometer (FHS). FHS is a double focusing magnetic channel consisting of two dipole and two pair of quadrupole magnets. The acceptance of the spectrometer was equal to 0.8 msr. Multiwire proportional chamber located at the second focus of the magnetic system served for the control of the secondary particle profile. The trigger for the events included signal from differential Cherenkov counter and signals from two-stage TOF system based on the scintillation counters. Two photomultipliers XP2020 were mounted on both sides of each scintillator. The resolution of the TOF system was 200 ps (sigma).Veto signal from gaseous Cherenkov counter was used for additional pion suppression. The particle identification was quite reliable up to the value of $K^+/(\pi^+ + p)$ ratio $1 : 6 * 10^7$ at the downstream TOF counter. The kaon missidentification was less than 5% for projectile proton energy range 2.9-1.7 GeV and did not exceed 15% for two lowest points. Special π-trigger was also prepared to measure the pion yields.

The measurements of K^+/π^+ ratios covered the initial proton energy range from 2.91 to 1.65 GeV. Eight activation experiments in the relevant range of energies were performed for determination of pion cross sections. The resulting uncertainty of absolute normalization of the differential cross sections for kaon production was equal to be 20%. Obtained values of the cross sections were corrected for the particles loss due to nuclear interactions with material in the spectrometer, multiple scattering, meson decays and detector efficiency. The measured differential cross sections for K^+ production from different nuclei are summarized in Table 1.

The example of energy dependence of K^+ cross section production on the Be target is presented in Fig.3. As it is seen the value of the cross section changes by five order of magnitude within the plotted range of incident proton energy. The right arrow indicates the threshold energy for the production of K^+ with detected parameters in free nucleon-nucleon collisions, while left arrow shows the absolute kinematical limit for K^+ production on Be nucleus.

4. DIRECT KAON PRODUCTION

We start the data analysis assuming the dominance of the direct production mechanism. The evidences for that will be presented in the next section.

Within the framework of the folding model [5,6,7,8] the invariant cross section for K^+ production in proton-nucleus collisions via direct channel can be expressed as a convolution of the internal nucleon momentum distribution n(q) and the kaon elementary cross section at invariant collision energy $S^{1/2}$ in the interaction of the projectile proton with target nucleon:

$$E\frac{d\sigma^{pA\to K^+X}(\mathbf{p}_0,\mathbf{p}_K)}{d\mathbf{p}_K} = N_1 \int_{q_{min}} d\mathbf{q}n(\mathbf{q})[\frac{E_K d\sigma^{pN\to K^+\Lambda N}(S,\mathbf{p}_K)}{d\mathbf{p}_K} + \\ + \frac{E_K d\sigma^{pN\to K^+\Sigma N}(S,\mathbf{p}_K)}{d\mathbf{p}_K}] \quad (4)$$

Here the expression in brackets stand for the cross sections for associated kaon production with Λ or Σ hyperon in the elementary proton-nucleon interactions, N_1 is a factor which accounts for the effective number of nucleons inside nucleus A as well as the absorption of the produced kaons when propagating through the nuclear target.

4.1. KINEMATICS

The energy-momentum relation is treated as being on-shell for projectile proton. The collision energy squared S is determined by the following expression (Fig.1a):

$$S = (E_0 + w)^2 - (\mathbf{P}_0 + \mathbf{q})^2, \quad (5)$$

where E_0,$\mathbf{P}_0$ and w,$\mathbf{q}$ are defined as total energy and momentum of the beam and target nucleon, respectively. The energy of the off-shell struck nucleon w can be obtained taking into account the recoil of the residual A-1 nucleon system:

$$w = M_A - E_{A-1}; \qquad \mathbf{q} = -\mathbf{q}_{A-1}; \quad (6)$$

The energy of this system is assumed to be minimal that correspond to the production of the nucleus A-1 with zero excitation energy in the final state:

$$E_{A-1} = M_{A-1} + \mathbf{q}^2/2M_{A-1}. \quad (7)$$

In the Eqs. (6),(7) M_A and M_{A-1} stand for the rest mass of A and A-1 nuclei.
From (6),(7) one has:

$$w = M_N - \mathbf{q}^2/2M_{A-1} - (M_{A-1} + M_N - M_A) \qquad or \tag{8}$$

$$w = M_N - E_R, \tag{9}$$

where M_N being the mass of free nucleon.

The nucleon removal energy:

$$E_R = \mathbf{q}^2/2M_{A-1} + \epsilon \tag{10}$$

The value of ϵ is accepted to be 1.6 MeV - the minimal nucleon binding energy in the studied nuclei. Above definition of w is motivated by the goal to find the lowest possible contribution of the high momentum component to n(**q**).

4.2. ELEMENTARY CROSS SECTION

A very important ingredient for the calculation of the cross sections in proton-nucleus collisions is the elementary cross section for kaon production. We use the free elementary cross sections as measured in proton-proton collisions. In order to apply its to the proton-nucleus case it is assumed that K^+ meson production cross sections in pp and pn-interactions are the same.

Data on differential cross sections of inclusive kaon production in the initial energy range 2.3- 2.9 GeV were obtained in [9,10]. The measurements covered the angular interval 8 - 40 degree in lab. Note, that kaon momentum $\mathbf{P}_K$ detected in our experiment pertains to the investigated kinematical range. The analysis of the above data shows that K^+ differential cross sections depends only on the invariant mass of hyperon-nucleon system . In the interval of invariant mass from the thresholds ($M_\Lambda + M_N$=2.054 GeV) to 2.10 GeV the measured cross sections for kaon production significantly exceed those calculated as tree-body phase space factor of the reaction $p+p \to K^+ + \Lambda + p$ [9]. An observed excess associated with final state ΛN interaction at low relative momenta agrees well with the theoretical expectations [11]. By the calculations in this mass range we use the measured cross sections $d^2\sigma/dM_{\Lambda N}d\Omega_K$ [9] related to the invariant cross sections appearing in (4) by the following relation:

$$\frac{d^2\sigma^{pp\to K^+\Lambda p}}{dM_{\Lambda N}d\Omega_K} = E_K\frac{d\sigma^{pN\to K^+\Lambda N}}{d\mathbf{p}_K}\frac{p_K^2 M_{\Lambda N}}{(E_0+m)p_K - p_0E_K cos\theta_K} \quad (11)$$

where θ_K denotes the kaon emission angle in the laboratory system, $p_K = |\mathbf{p}_K|$, $p_0 = |\mathbf{p}_0|$

At M_{YN} >2.10 GeV K$^+$ cross section in the angular interval 10 - 40 degree can be approximated within 15% accuracy as:

$$E_K\frac{d\sigma^{pN\to K^+YN}}{dp_K} = \frac{|T_\Lambda|^2R_2(M_{\Lambda N}^2, M_\Lambda^2, M_N^2) + |T_\Sigma|^2R_2(M_{\Sigma N}^2, M_\Sigma^2, M_N^2)}{F(S)} \times (12)$$

$$\times\,[1 + 8.5\frac{M_{YN} - 2.2GeV}{2.2GeV}\theta(M_{YN} - 2.2)], \qquad mkbGeV^{-2}sr^{-1}c^3$$

Here F stands for the flux factor, R_2 is two-body phase space factor for associated kaon production with Λ or Σ hyperon. The values of the matrix elements obtained by the fitting to the data [9,10] are found to be

$$|T_\Lambda|^2 = 170mkb \quad , \quad |T_\Sigma|^2 = 340mkb \quad (13)$$

The expression in brackets accounts for increase in K$^+$ production rate at M_{YN} >2.20 GeV [10] since processes with one and more pions in the final state also can contribute to the inclusive cross section.

Thus, the analysis of data [9,10] shows that elementary kaon production cross section does not follow the phase space factor of the exclusive reaction p+$p \to K+Y+N$ both at near threshold and well above threshold energies. Flux factor F is calculated at invariant collision energy $S^{1/2}$ in pp equal to that for the interaction of primary proton with target nucleon:

$$F = P_0^{'}M_N, \quad (14)$$

where proton momentum $P_0^{'}$ is determined by the following relation:

$$S = 2M_N^2 + 2M_N\sqrt{(P_0^{'2} + M_N^2)}, \quad (15)$$

The quantity S entering into Eq.(15) is defined above by the formulae (5).

4.3. NUCLEON MOMENTUM DISTRIBUTION

Internal nucleon momentum distribution can be represented in the following form depending on tree parameters σ_1,σ_2, h :

$$n(q) = \frac{1}{(2\pi)^{3/2}(1+h)}[\frac{1}{\sigma_1^3}exp(\frac{-q^2}{2\sigma_1^2}) + \frac{h}{\sigma_2^3}exp(\frac{-q^2}{2\sigma_2^2})] \qquad (16)$$

Here first term relates to the normal Fermi motion whereas second one to its high momentum component generated by the short-range nucleon-nucleon correlation. We adopt the normalization:

$$4\pi \int n(q)dq = 1. \qquad (17)$$

4.4. FACTORS N_1

In principal, the factors N_1 can be calculated within the Glauber approximation (see for example [7]). Numerical calculations for light Be nucleus assuming the Gaussian nuclear density distribution and taking into account σ_{in}^{pN}=30 mb, σ_{in}^{KN}=12 mb comes to N_1=5.2. However the account for kaon absorption inside nuclear medium especially for heavy nuclei is still a matter of discussion. Therefore the values of N_1 are determined from the obtained experimental data as a ratios:

$$N_1 = \frac{E_K d\sigma^{pA\to K^+X}/d\mathrm{p}_K}{E_K d\sigma^{pp\to K^+X}/d\mathrm{p}_K} \qquad (18)$$

The data on kaon production in proton-nucleus collisions are taken from Table 1 at above threshold energy where direct production is obviously dominated and the influence of the Fermi motion on the values of the cross section is small. As it was found in [10] the K^+ double differential cross sections in proton-proton collisions exhibit the isotropic behavior in the center of mass system. Thus the kaon production rate at fixed collision energy depends only on K^+ momentum in the above system. That provides the possibility to calculate the cross section of kaon production in the elementary reaction for the kinematical condition of the present experiment. The values of N_1 averaged over projectile proton energy range 2.54 - 2.88 GeV are listed in Table 2. Note that the obtained value of N_1 for Be nucleus agrees well with that calculated within the Glauber approximation. Moreover above agreement supports our assumption that K^+ meson production cross sections in pp and pn-interactions are the same.

Table 1

Invariant cross sections $Ed\sigma/d^3p$ $[nbGeV^{-2}sr^{-1}c^3]$ for K^+ production with momentum 1.28 GeV/c at 10.5 degree (lab) on Be, Al, Cu and Ta. Unspecified errors are less than 15%. The uncertainty of the absolute normalization (see text) is not included.

T_0	Be	AL	Cu	Ta
2.910	6.87E5	1.54E6	1.99E6	
2.800	5.57E5	1.11E6	1.43E6	
2.700	4.44E5		1.21E6	
2.600	3.42E5	7.30E5	1.02E6	1.78E6
2.500	2.61E5	6.50E5	8.12E5	1.31E6
2.400	2.07E5	4.45E5	6.71E5	1.02E6
2.300	1.44E5	3.43E5	4.78E5	6.50E5
2.200	8.80E4	2.04E5	2.66E5	4.30E5
2.100	5.50E4	1.15E5	1.49E5	2.50E5
2.000	2.23E4	5.57E4	7.66E4	1.15E5
1.900	8.79E3	2.45E4	3.49E4	3.62E4
1.850	3.43E3	1.09E4	1.41E4	1.81E4
1.825	1.95E3	6.46E3	1.07E4	1.15E4
1.800	1.18E3	4.55E3	7.37E3	5.52E3
1.775	6.67E2	2.29E3	3.42E3	
1.750	4.17E2	1.37E3	1.98E3	1.85E3
1.725	1.67E2	5.92E2	9.04E2	
1.700	7.17E1	2.47E2	3.40E2	
1.675	1.67E1	1.14E2	8.71E1	
	± 3.7E0	± 23E0	± 2.7E1	
1.650	5.50E0	4.20E1		
	± 2.5E0	± 1.47E1		

Table 2

Parameters of the nucleon momentum disributions $n(q)$.

A	Be	AL	Cu	Ta
N_1	4.9± 0.4	10.4± 1.0	13.5± 1.0	21.0± 2.0
$\sigma_1, MeV/c$	136± 11	149± 11	150± 12	145± 10
$\sigma_2, MeV/c$	212± 17	208± 18	200± 18	
h	0.1	0.1	0.1	0.0

4.5. COMPARISON WITH DATA

The parameters of the nucleon momentum distributions n(q) for investigated nuclei in the form (16) were determined by fitting to the data on energy dependencies of the cross sections by (4)-(18) using the MINUIT code. It was found that there exist many sets of parameters σ_1, σ_2 and h providing good description of data. In fact the measured energy dependencies can be roughly reproduced (χ^2/d.o.f. about 3-4) using the simple form of the $n(q) = const * exp(-q^2/2(\sigma_0^2))$ with σ_0=0.15-0.17 GeV/c. In order to make a statement about the values of the parameters we fixed the parameter h=0.10. The results of such fits are presented in Table 2. High momentum part of the n(q) for Ta nucleus can not be found since the data were obtained in limited primary proton energy range. The uncertainties of the parameters σ_1 and σ_2 listed in Table 2 correspond to one-standart-deviation errors. The fit to the data obtained on Be target is shown in Fig.3 by the solid curve. The value of χ^2/d.o.f. is less about 1. Similar calculation including the elementary cross section proportional to the reaction phase space yields the increase of χ^2/d.o.f. by a factor of 4 (dashed line in Fig.3). It should be noted that account for the effect of final state interaction is essential for the description of data especially at deep subthreshold energies.

Calculations show that the relative strength of the ΛN and ΣN channels are comparable at initial proton energies 2.3-2.4 GeV whereas ΛN channel dominates below 1.8 GeV.

5. EVIDENCES FOR PREVALENCE OF DIRECT MECHANISM

5.1. CROSS SECTION CALCULATION

Within the frame of the folding model the invariant cross section for K^+ meson cascade production in proton-nucleus collisions (Fig.1b) can be expressed as a convolution of the probability for pion production in proton-nucleus collisions and the elementary cross section for K^+ production in pion induced reaction written in the form similar to that for proton induced process (see (4)):

$$[E_K \frac{d\sigma^{pA\to K^+X}(\mathbf{p}_0,\mathbf{p}_K)}{d\mathbf{p}_K}]^{casc} = 2N_2 \int d\mathbf{p}_\pi \frac{d\sigma^{pA\to\pi X}(\mathbf{p}_0,\mathbf{p}_\pi)}{d\mathbf{p}_\pi}\frac{1}{\sigma^{pA}_{tot}} \times \quad (19)$$
$$\times\, d\mathbf{q} n(\mathbf{q})[E_K \frac{d\sigma^{\pi N\to K^+Y}(\sqrt{S_1},\mathbf{p}_K)}{d\mathbf{p}_K}]$$

Here S_1 stands for invariant energy available in the collision of pion with off-shall target nucleon:

$$S_1 = (E_\pi + w)^2 - (\mathbf{P}_\pi + \mathbf{q})^2 \quad (20)$$

The calculation including the nucleon momentum distribution n(q) obtained in Sec.4 were performed for light Be nucleus using the value of total cross section σ^{pBe}_{tot}=170 mb. Factor N_2 can be represented in the following form:

$$N_2 = N_1 * \nu, \quad (21)$$

where ν stands for the probability of pion inelastic interaction inside the nucleus of radius R [5]:

$$\nu = (R^2 - l^2/4)/R^2 \quad (22)$$

Here l=3.2 fm is a pion pass length before the collision. Coefficient 2 in Eq.(19) accounts for the contribution to the cross section from neutral pions.

The missing now data on differential cross section of the $pA \to \pi X$ reactions close to the absolute kinematical limit are required for the calculation of integral (19). Therefore we had to perform special measurements of the differential cross sections for π^+ and π^- production on Be target at outgoing pion laboratory angle 10.5 degree. The obtained data taken at projectile proton energies 1.7 and 2.25 GeV covered the interval of radial Feynman's variable $0.50 < X^R_F < 0.95$. The cross sections for positive and negative pion production exhibit the scaling behavior with respect to X^R_F with accuracy of a factor of 2. Similar behavior of the cross sections was early observed in [12] for zero degree π^- production. Using the available and newly obtained data the pion cross sections in angular interval 0-15 degree can be approximated as follows:

$$E_{\pi^+}\frac{d\sigma^{pBe\to\pi^+X}}{d\mathbf{p}_{\pi^+}} = 220(1 - X^R_F)^{3+3P_t^2}, \qquad mbGeV^{-2}sr^{-1}c^3 \quad (23)$$

where P_t stands for the transverse component of pion momentum.
The inclusive cross section for K^+ production in pion induced reaction appearing in (19) is calculated following the prescription given in [7]. For the total cross sections $\sigma^{\pi N \to K^+ \Lambda}$ and $\sigma^{\pi N \to K^+ \Sigma}$ we use the parametrizations suggested in [13] and [14], respectively.

In Fig.3 the dash-dotted line represents the result of the calculation of the cross section for cascade kaon production by (19)-(23). It is clearly seen that two-step mechanism plays a minor role in the kinematics of present experiment.

5.2. ATOMIC MASS DEPENDENCE

Let us estimate the possible contribution of the cascade channel to the cross sections for subthreshold kaon production on middle and heavy nuclei. The ratios of experimental invariant K^+ production cross sections on nucleus A and the same values on Be nucleus denoted as R(A/Be) are plotted in Fig.4 against the atomic mass number A. The lines in the figure represent the results of the calculations of the above ratios for two competing mechanisms within the simple model which take into account only absorption effect for projectile proton, intermediate pion (for two-step channel) and outgoing kaon. According to the model the target atomic mass cross section dependence for cascade channel is stronger compared to that for direct channel. As to the experimental data it is clearly seen that the values of R(A/Be) measured in the present study are significantly less than corresponding values observed in [1]. Remind that in the kinematics of experiment [1] the kaon yield is completely determined by the cascade mechanism[5,6,7].

In the above threshold range at projectile proton energies 2.2 - 2.6 GeV where direct channel obviously dominates the calculations agree well with the data. Below 1.8 GeV the measured values of R(Al/Be) and R(Cu/Be) increase by a factor of 1.5. One of the possible reason for that is a difference between the nucleon momentum distribution in light and middle nuclei. This property of the nuclei is disregarded by the applied simple model. The assumption that the opening of the cascade channel is a single reason for observed enlargement of R provides the possibility to estimate the maximal contribution of the cascade production to the cross sections.

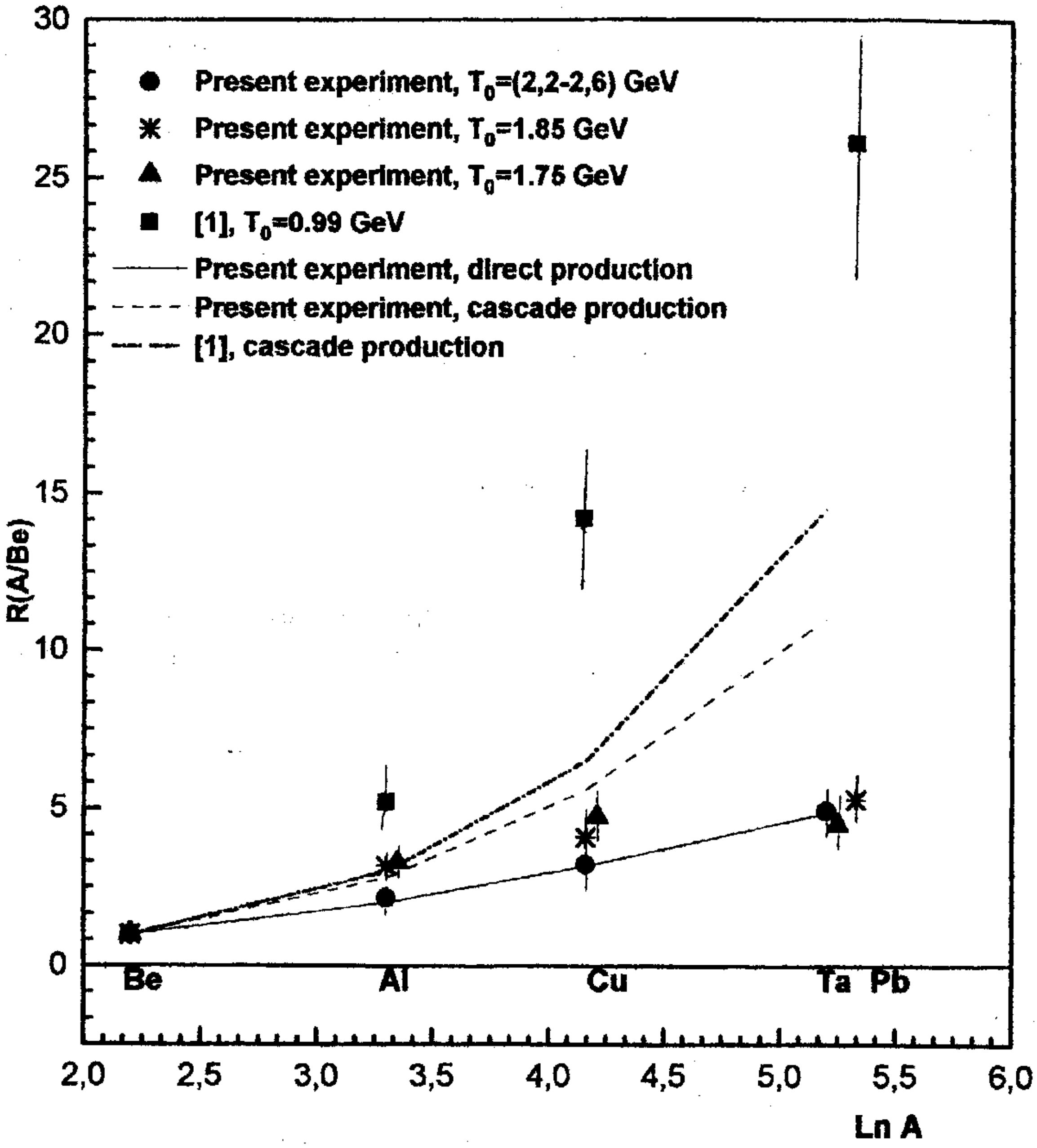

Fig.4. Atomic mass dependence of subthreshold kaon production.

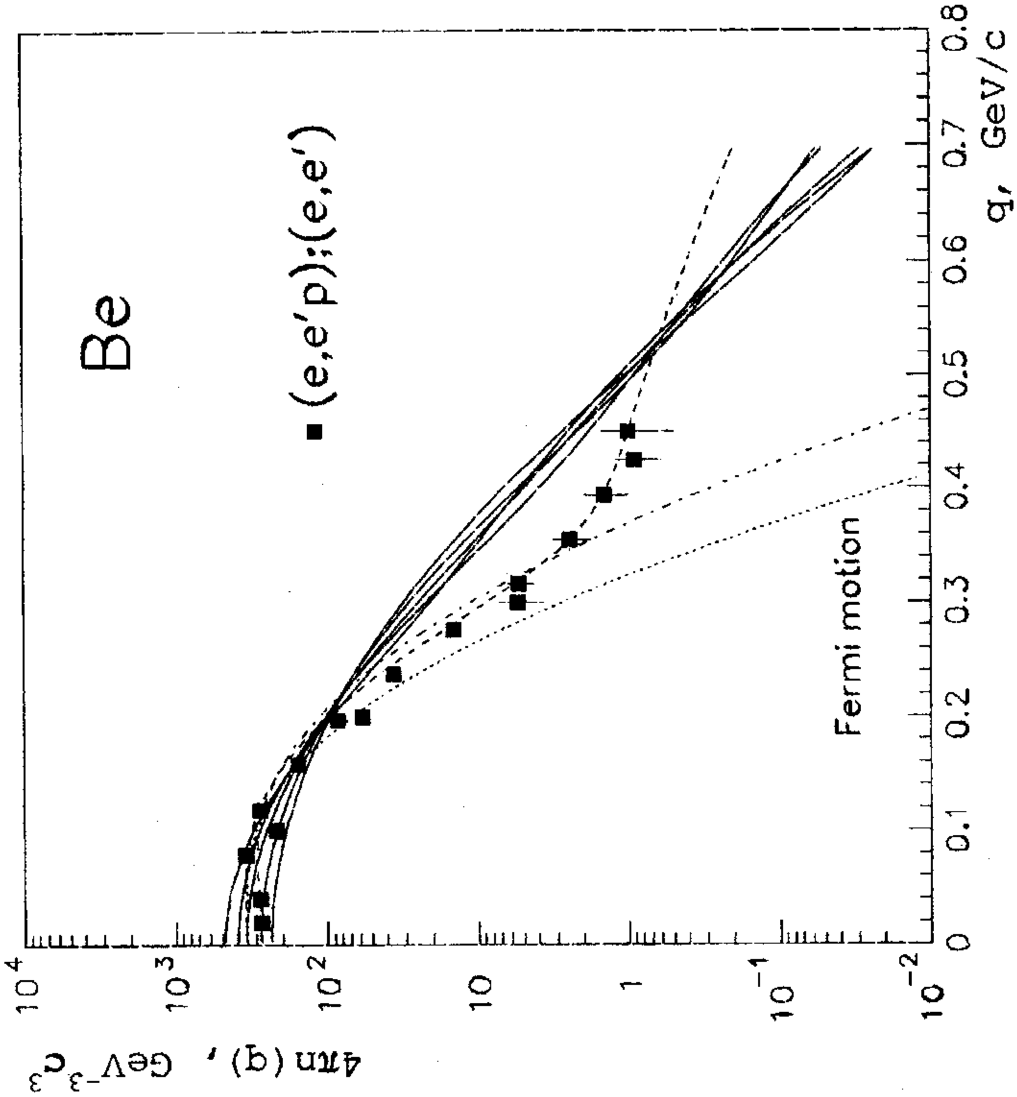

Fig.5. Nucleon momentum distribution for Be.

Taking into account the result obtained in Sec. 5.1 for the light Be nucleus one can easily find that these contributions for Al and Cu nuclei are about 1/3. Observed independence of R(Ta/Be) on initial proton energy suggests that cascade mechanism might plays a minor role in the subthreshold kaon production process on heavy nuclei.

6. NUCLEON MOMENTUM DISTRIBUTIONS

The nucleon momentum distribution n(q) for Be nucleus extracted from the fit to the energy dependence of the cross sections is shown in Fig.5. Bunch of the long-dashed curves reflects the uncertainties of the extracted parameters. The obtained distribution is extended up to momenta about 700 MeV/c since the threshold internal nucleon momentum q_{min} exceeds 640 MeV/c by the cross section calculation at the lowest proton beam energy 1.65 GeV.

It should be emphasized that the distribution presented in Fig.5 corresponds to the minimal possible contribution of high momentum component to n(q) because of minimal values of the removal energies are incorporated in the fitting procedure. Inserting into Eq.(10) the average binding energy per nucleon, as well as taking into account the possible excitation or fragmentation of the residual (A-1) system leads to the growth of Er and as a consequence to the fall of a struck nucleon energy. The result of the calculation including E_R increased by 10 MeV exhibits the noticeable underestimation the measured cross sections below the threshold. Enhanced values of the high momentum component parameters are needed for restoration of the accordance with the data. Besides above enlargement of Er results in the shift of threshold internal nucleon momentum up to 706 MeV/c at the lowest proton energy.

For comparison the Fermi distribution is shown in Fig.5 by the dotted line. Essential contribution of the high momentum component to n(q) at momenta above 250 MeV/c is clearly seen. The results of the analysis of $(e, e'p)$ and (e, e') reactions on carbon target taken from [15] are depicted by the black squares. The nucleon momentum distribution extracted from the data of present experiment coincides well with that obtained from the electron induced processes up to momenta about 250 MeV/c while the above two distributions definitely disagree in the momentum range 300-

450 MeV/c. However such straightforward comparison can not be quite correct since it use the data obtained in somewhat different intervals of E_R.

6.1. SPECTRAL FUNCTION

The recent theoretical advances in study of short-range properties of the nuclear structure [15,16] have provided a concept of a spectral function. The nucleon spectral function S(q.E_R) represents the joint probability of finding a proton of momentum q within nucleus and leaving the residual system excited by energy E_R. Function S(q.E_R) contains all the information on the structure of a target nucleus.
The nucleon momentum distribution n(q) related to S(q.E_R) by

$$n(q) = \int_{E_{thr}}^{E_{max}} S(q, E_R) dE_R \qquad (24)$$

where E_{thr} is the single nucleon removal threshold. The functions (24) for carbon target when integrating up to energy E_{max}=40 and 500 MeV are presented in Fig.5 by dash-dotted and dashed lines, respectively. The difference between the lines is caused by strong correlation q and E_R at momenta above 350-400 MeV/c. Taking into account the energy balance of the production process one can expect that the distribution extracted from the data of present experiment would be close to the dash-dotted curve because of the energy loss grater than 40-60 MeV is kinematically forbidden in deep subthreshold range. However, it is seen that the dash-dotted curve lie far below the bunch of the long-dashed lines representing the extracted nucleon momentum distribution. This observation evidences for the existing models of the nucleon spectral function underpredict the strength of the high momentum component at momenta above 300 MeV/c. Indeed, the calculation by (4) with n(q) replaced by S(q,E_R) fails completely to reproduce experiment in deep subthreshold region (crosses in Fig.3).

The reason behind this is a different treatment of the off-shell effect in two approaches under consideration. According the model of the nucleon spectral function [15] the mean removal energy

$$< E_R >= 2\epsilon + q^2/2M_N, \qquad \epsilon = 7MeV \qquad (25)$$

is much grater than that used in the performed calculation by Eq.(10). As a consequence, the cross sections for kaon production calculated in the spectral function approach appears to be suppressed.

However, as it was shown in [17] the results of the present experiment can be reproduced quite well by the calculations in the framework of the folding model based on nucleon spectral function which take properly into account the effective nucleon and hyperon mean-field potentials within the nuclear matter.

7. SUMMARY

We have measured the initial proton energy dependence of the differential cross sections for subthreshold and near threshold K^+ production of momentum 1.28 GeV/c at laboratory angle 10.5 degree on Be, Al, Cu and Ta nuclei. It was shown that in the kinematical region of the performed experiment direct kaon production mechanism clearly dominates over cascade one. The internal nucleon momentum distributions extracted from the data were extended up to 700 MeV/c. Existing models of nucleon spectral functions disregarding any in-medium effects fail to reproduce the measured energy dependencies. New data covering a wider range of experimental conditions as well as more complete theoretical calculations are required to reach a better understanding of the possibility to study the short-range properties of nuclear matter in the subthreshold processes.

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