Subthreshold K^+ production in the interaction of 1-GeV protons with Be, C, Al, Cu, Sn, and Pb nuclei

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A new method is described for studying the "subthreshold" production of K^+ mesons. The μ^+ mesons from the K^+ mesons stopped in the target are detected, and the microstructure of the proton beam is used. The total cross sections for K^+ production have been mesured for the interaction of 1-GeV protons with Be, C, Al, Cu, Sn, and Pb nuclei.

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Cumulative processes in nucleon-nucleus interactions, which can furnish information about many-nucleon correlations in nuclei, have recently attracted increased interest in intermediate- and high-energy physics. Particularly interesting in this regard are reactions involving the "subthreshold" production of particles, e.g., reactions which produce K^+ mesons in nucleon-nucleus interactions (the threshold energy is 1582 MeV). The small production cross sections and the short K^+ lifetime, however, present very serious experimental difficulties, and as a result absolutely no data have been reported on the subthreshold production of K^+ mesons.

Our purpose in the present work was to develop a new method and to obtain the first experimental data on the total cross sections for K^+ production in proton-nucleus interactions at an incident-proton energy of 1 GeV (Refs. 1 and 2).

To a large extent, the difficulties in measuring the total cross sections for K^+ production were overcome by adopting a new method for studying the subthreshold production K^+ mesons. The K^+ mesons are identified on the basis of the monoenergetic μ^+ mesons produced in the two-particle decay $K^+ \to \mu^+ \nu$ of the K^+ mesons stopped in the target. The μ mesons with a momentum $P_\mu = 236$ MeV/c, which corresponds to the decay of a K^+ meson at rest, are singled out with a magnetic spectrometer. A ΔE, E analysis distinguishes μ^+ mesons form π^+ and e^+. A time-of-flight analysis based on the discontinuous temporal structure of the proton beam of the synchrocyclotron makes it possible to distinguish μ^+ mesons with $P_\mu = 2336$ MeV/c resulting from the decay of K^+ mesons stopped in the target, on the one hand, from μ^+ mesons resulting from the decay of moving π^+ mesons. The μ^+ mesons from the K^+ decay have a characteristic exponential distribution in the gaps between the microbunches of μ^+ mesons resulting from the decay of moving π^+ mesons (Fig. 1). The quality of this discrimination of useful events depends on the background of extracted protons in the intervals between the microbunches; in the synchrocyclotron of the Leningrad Institute of Nuclear Physics, in a time interval of 40 ns, this background did not exceed 10^{-6} of the proton flux of the main beam. It was thus possible to

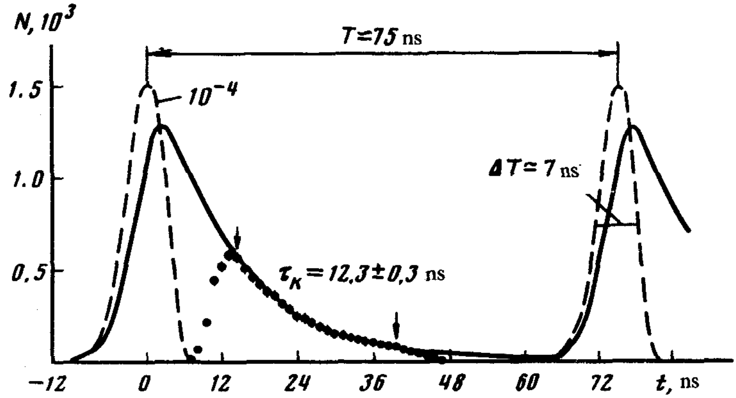

FIG. 1. Temporal distribution of the μ^+ mesons at the exit from the spectrometer. Dashed curve—μ^+ mesons from the decay of moving π^+ mesons; ΔT—length of a microbunch : T—rf period of the accelerator; solid curve—calculated temporal distribution of μ^+ mesons from K^+ decay; filled circles—experimental points measured in a 40-ns time window. The parameter τ_K was determined by the method of least squares from the experimental points in the interval between the arrows.

distinguish the μ^+ mesons resulting from the decay $K^+ \to \mu^+ \nu$ within an error of 3%. Figure 2 shows μ^+ momentum spectrum measured by the π-meson channels of the synchrocyclotron for emission angles of 60° and 0° (Refs. 3 and 4). The positions and width of the peaks are determined by the kinematics of the decay $K^+ \to \mu^+ \nu$, by the momentum resolution of the spectrometers, and by the energy loss of the μ^+ mesons in the target. The absence of a corresponding peak from the spectrum of μ^- mesons (angle of 60°) is attributed to the much higher energy threshold for the production K^- mesons and to the capture of K^- mesons by nuclei. Further confirmation of the production of subthreshold K^+ comes from the observation of the temporal distribution of the μ^+ mesons, measured in a 40-ns time window (Fig. 1). It was found that

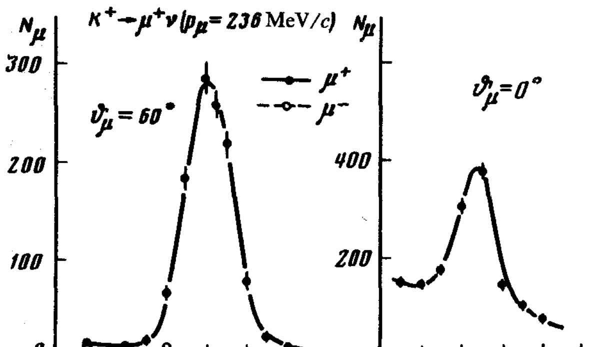

FIG. 2. Momentum spectra μ^+ mesons in a 40-ns time window for emission angles of 60° and 0° from a carbon target 60 mm in diameter and 30 mm thick.

these μ^+ mesons have an exponential distribution with a constant of 12.3 ns, which agrees with the tabulated lifetime of K mesons.

After establishing the fact that subthreshold K^+ mesons were produced, we turned to a determination of the reaction channel. In our case the K^+ mesons could be produced in nucleon-nucleus collisions [reaction (1) below] or as a result of a two-step process consisting of the production of π^+ mesons with an energy above 53 MeV, followed by the production of K^+ mesons by these π^+ mesons [reaction (2)]:

$$PA \to K^+ \Lambda A, \quad (1)$$

$$\pi^+ A \to K^+ \Lambda (A-1). \quad (2)$$

Two experiments were carried out to identify the primary channel. In the first experiment we compared the yield of μ^+ mesons resulting from K^+ decay from CH_2 and C targets with equivalent amounts of carbon. The ratio N_μ $(CH_2)/N_\mu$ (C) turned out to be one (0.98‾0.05), indicating that the K^+ mesons are produced only in the carbon. In the same experiment we found the following ratio for the π mesons: N_π $(CH_2)/N_\pi(C) = 1.69 \pm 0.03$. In the second experiment we measured the yield of π and μ mesons for various thickness of the carbon target. For K^+ production by channel (1) the μ^+ yield should be proportional to the target thickness, while for channel (2) it should vary quadratically with the thickness. The experiment showed that the μ^+ yield varies in proportion to the target thickness. On the basis of these two experiments it may thus be asserted that the K^+ mesons are produced as a result of direct nucleon-nucleus interactions, in reaction (1).

To find the boundary of the energy spectrum of the K^+ mesons produced, we measured the yield of delayed μ^+ mesons as a function of the thickness of the carbon absorber stopping the K^+ mesons. This absorber was positioned outside the zone affected by the proton beam. At an absorber thickness of 2 cm (3.2 g/cm^2) the yield reached saturation; this effect corresponded to the stopping of the most of the K^+ mesons in the target (1.6 G/cm^2) and the absorber. It may thus be concluded that the maximum energy of the K^+ mesons which makes a significant contribution to the total cross sections for reaction (1) does not exceed 60 MeV.

Figure 3 shows the total cross sections for K^+ production in nuclei found from these experiments. According to these data, the cross sections for the subthreshold production of K^+ mesons at a proton energy of 1 GeV are comparatively large, ranging from 2×10^{-32} to 6×10^{-31} cm^2. The relative error of the results is determined primarily by the statistical errors ($\pm$ 3%). The absolute values of the cross sections are established within 30%. It is interesting to note that 1 GeV is the threshold for the production of K^+ mesons in the free three-nucleon syustem (^{3}H, ^{3}He). For K^+ production in nucleon-nucleon collisions, the nuclear nucleon must have a momentum above 375 MeV/c in the direction opposite the incident proton. The production of K^+ mesons in Pd colllisions at $T_p = 1$GeV is possible only if the pair of nuclear nucleons has a momentum above 150 MeV/c.

This behavior of the K^+ production cross section as a function of the atomic number of the nucleus and a comparison of this behavior with that for π^+ mesons indicate that the deep subthreshold production of K^+ mesons is apparently due to

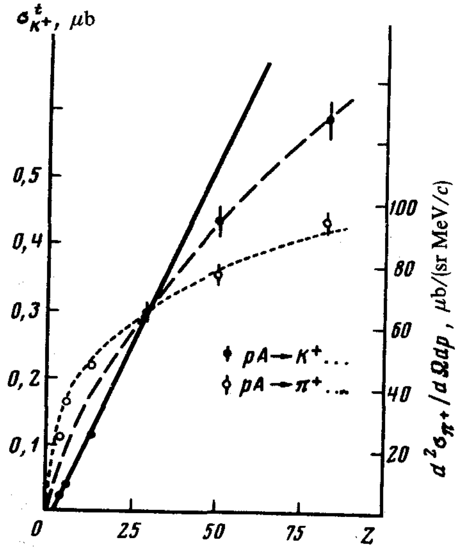

FIG. 3. Filled circles—total cross sections for the production of K^+ mesons; open circles—double differential cross sections for the production of π^+ mesons with a momentum of 230 MeV/c at an angle of 60° from Be, C, Al, Cu, Sn, and Pb. Solid curve—$\sigma \sim Z - 2$; dashed curve—$\sigma\ z^{2/3}$ (Ref. 3); dotted curve—$\sigma \sim z^{1/3}$. The curves are normalized to the experimental data for the nucleus with charge $z = 29$ (Cu).

collective states of the nucleons in the nuclear matter. Measurements are currently being carried out at $T_p < 1$ GeV to identify the mechanism for the production of K^+ mesons.

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