Cascade mechanism for subthreshold production of K^+ mesons in proton-nucleus interactions

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At an incident-proton energy in the range 900–1000 MeV, the two-step mechanism involving the production of a pion in an intermediate state is the governing mechanism for the production of K^+ mesons in proton-nucleus interactions.

In recent years, it has become one of the basic directions in research on nuclear reactions at intermediate energies of the initial particles to search for processes which cannot be explained in terms of the conventional single-particle representations of the structure of the nucleus and the mechanism for nuclear reactions. In a description of the reactions involving a subthreshold production of antiprotons, the governing mechanism is a two-step mechanism in whose first step a pion is produced ($pN \rightarrow \pi NN$), followed by the production of an antiproton in a pion-nucleon interaction[1] ($\pi N \rightarrow \bar{p}pN$). A mechanism involving the production of a pion in an intermediate state is also important in describing the production of K^- mesons in the collisions of relativistic nuclei[2] and in reactions involving the production of cumulative particles.[3] It is thus worthwhile to study in detail the contribution of the two-step mechanism to the cross sections for reactions involving the subthreshold production of K^+ mesons in proton-nucleus interactions, for which the experimental information available is currently the most comprehensive.[4,5]

In this case the two-step mechanism can be described as follows: A pion is produced in the first step ($pN \rightarrow \pi NN$), while in the second a K^+ meson is produced ($\pi N \rightarrow K^+\Lambda$). Simple estimates show that the threshold for the two-step mechanism is below the threshold for the direct mechanism ($pN \rightarrow NK^+\Lambda$), while the incorporation of the Fermi motion of the nucleons in the nucleus may cause the two-step mechanism to contribute to the cross section for the production of a K^+ meson at all energies of the initial protons for which experimental data are available (800–1000 MeV), while the direct mechanism may contribute only when there is a high-momentum component in the distribution of nucleons of the nucleus.

The following approximations are used in the present calculations of the cross sections for the production of K^+ mesons: 1) The propagation of pions and nucleons in the nucleus is described in semiclassical terms. 2) The free cross sections for the production of pions in nucleon-nucleon collisions are used; the process $pp \rightarrow \pi^+ d$ is not taken into account here. 3) The momentum distribution of the nucleons in the nucleus is described by the Fermi-gas model, which is justified in a semiclassical description of the nuclear reactions which do not require a high-momentum component. 4) The cross section for the production of K^+ mesons is approximated by an expression which reproduces the experimental data quite well[6]:

$$\sigma(\pi N\rightarrow K\Lambda)=\begin{cases}0, & E< 767\ \mathrm{MeV}\\ 6.6\times 10^{-30}\ (E-767)\ \mathrm{cm}^2, & 767\ \mathrm{MeV}< E< 877\ \mathrm{MeV},\\ 7.26\times 10^{-28}\ \mathrm{cm}^2, & 877\ \mathrm{MeV}< E,\end{cases}$$

where E is the kinetic energy of the pion in the rest frame of the nucleon. 5) We ignore the rescattering of K mesons in the nucleus.

For the energies of the nucleons and pions under consideration here, approximations 1)–3) describe the inelastic proton- and pion-nucleus interactions within 10%, and the model of intranuclear cascades can be used, as was shown in Ref. 7. Approximation 5) is justified since we are concerned here with the total cross sections for the production of K^+ mesons, and the incorporation of the charge exchange $K^+\rightleftharpoons K^0$ can change the result by no more than 10%, even for heavy nuclei, as estimates show. The results of the calculations are shown in Figs. 1–3. It can be seen in Fig. 1 that the mechanism under study here reproduces the behavior of the cross section as a function of the mass number (A) of the target nucleus quite well at a proton energy of 1 GeV.

Figure 1 shows the cross section for the production of K^+ mesons as a function of the proton energy for Pb and C nuclei. It should be noted that at a proton energy below 900 MeV the results of the calculations lie below the experimental data. This result can be explained by analyzing the momentum distribution of the nucleons of the nucleus which are involved in the production of K^+ mesons. While nucleons with all allowed momenta participate in the reaction at an incident-proton energy of 1 GeV (Fig. 3), the only nucleons that participate at 830–850 MeV are those whose momenta lie close to the boundary of the momentum distribution. The special role played by these momenta is particularly obvious in the process $\pi N\rightarrow K^+\Lambda$. It should be noted that, as the calculations show, the nuclear nucleons which basically participate in the reaction are those which are moving in the direction opposite the particle—the proton or pion—which is propagating through the nucleus.

We see that the Fermi-gas model is of little help for describing the high-momen-

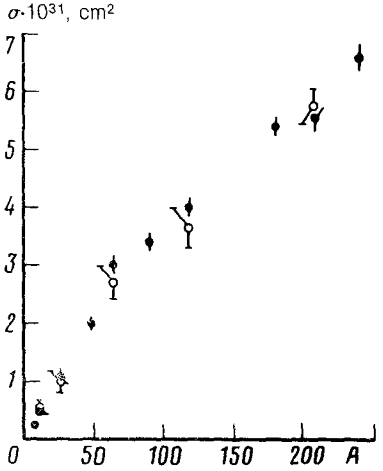

FIG. 1. Cross section for the production of K^+ mesons versus the mass number of the target nucleus. Filled circles—Experimental points from Ref. 5 for a proton energy of 0.99 GeV; open circles— results of the calculations.

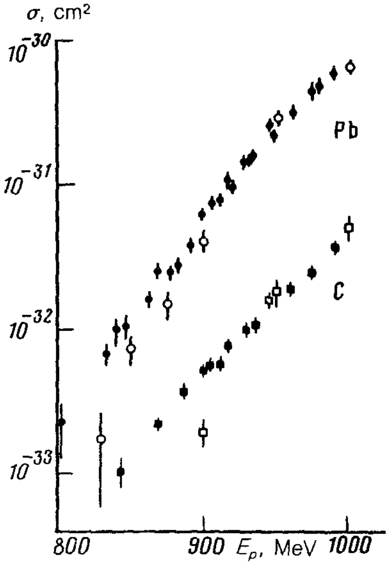

FIG. 2. Cross section for the production of K^+ mesons versus the energy of the initial protons for Pb and C nuclei. Filled symbols—Experimental points from Ref. 5; open symbols—results of the calculations.

tum component of nucleons in the nucleus. Consequently, the cascade mechanism for describing the subthreshold production of K^+ mesons leads to reliable results only at initial-proton energies in the range 900–1000 MeV. At lower energies, a description will require a more accurate incorporation of the high-momentum component of the nucleon distribution. This approach may eliminate the discrepancy between the calculated results and experimental data. As we mentioned earlier, we ignored the process $pp \rightarrow \pi^+ d$ in describing the pion production, and this simplification may increase the

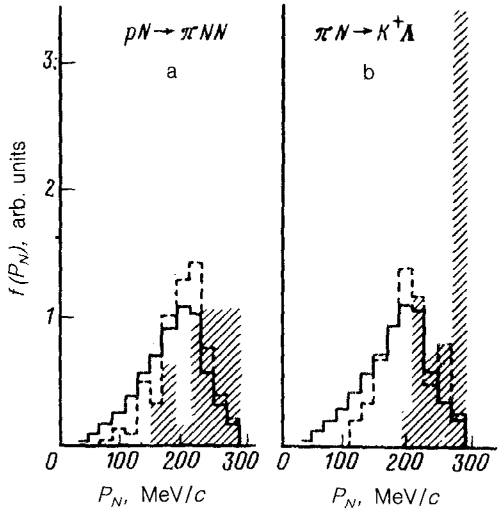

FIG. 3. Momentum distribution of the nucleons of the nucleus. Solid histogram: Initial distribution. Dashed histogram: For nucleons of the nucleus which are involved in the reaction at an initial-proton energy of 1 GeV. Hatching: Region of nucleon momenta at initial energies of 830–850 MeV. (a)—For the first step of the reaction ($pN \rightarrow \pi NN$) (b)—for the second step ($\pi N \rightarrow K^+\Lambda$).

cross section for the production of K^+ mesons by about 30%, provided, of course, that this process is not suppressed for some reason in the core of the nucleus.

The subthreshold production of K^+ mesons in pion-nucleus interactions appears to be the most promising reaction for a study of the high-momentum component of the distribution of nucleons in a nucleus, since the reaction in this case is a single-step reaction, and its cross section depends strongly on the assumptions regarding the high-momentum component in the distribution of nucleons in the nucleus at pion energies below 600 MeV. Calculations for a Pb nucleus show that the cross section for the reaction $\pi^+ + \mathrm{Pb} \to K^+$ is 4.8×10^{-29} cm^2 at a pion energy of 600 MeV.

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