Inclusive production of pions by protons in nuclei at low energies

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(Submitted April 6, 1980)
Pis'ma Zh. Eksp. Teor. Fiz. **31**, No. 11, 696–700 (5 June 1980)

The results of measurements of the inclusive production of π^+ mesons by protons in carbon and copper nuclei at an energy of 240 MeV, i.e., below the production threshold in a free nucleon, are satisfactorily described by calculations performed on the basis of an impulse approximation with distorted waves.

PACS numbers: 25.40. – h, 14.40.Dt

The production of pions by protons has been investigated in detail experimentally and theoretically[1–4] at the 600 to 800-MeV energies of the meson factories. It was shown that the key mechanism is the formation of a Δ_{33} isobar in the collision of an incident nucleon with nucleons of the nucleus and its subsequent decay with the emission of a pion.[4] At the same time, we can expect the appearance of interesting collective effects at lower energies; for example, the formation of bound isobaric states in the nucleus or dibaryon-type states. At energies below the threshold of meson formation the pion production cross section in free nucleons is completely determined by nucleon interaction effects in the nucleus. The inclusive pion spectra, nonetheless, were measured only at a few points at an energy above 340 MeV,[5,6] because of a sharp decrease of the pion yield with decreasing proton energy. Here, we shall not discuss the numerous papers on the study of the (p,π) reaction in nuclei, since the nucleus in this case remains in the ground state or a slightly excited state, whereas the inclusive spectra are due primarily to high-energy excitations. It is clear that the contribution of pion production in a simple model of the nucleus in the form of a degenerate Fermi gas of nucleons, must be initially isolated in the search for any new type of excitations in the pion production process. This paper is an attempt to study experimentally and theoretically the inclusive production of pions in carbon and copper nuclei at proton energies of 240–500 MeV.

The measurements were performed in the proton beam of the synchrocyclotron of the Joint Institute for Nuclear Research Laboratory of Nuclear Problems. A two-dimensional analysis of the transit time and energy, based on thin scintillation counters and a total absorption detector, was used to identify the π^+ mesons and measure their energy. Because of the superposition on the pion spectrum of inelastically scattered, high-intensity protons that have undergone a nuclear interaction with the detector material, we limited the pion spectra to 30 MeV on the low-energy side. As follows from an extrapolation of literature data,[5] the π^- meson impurity in the spectrum amounts to $\leqslant 10\%$. In determining the binary differential cross sections from the

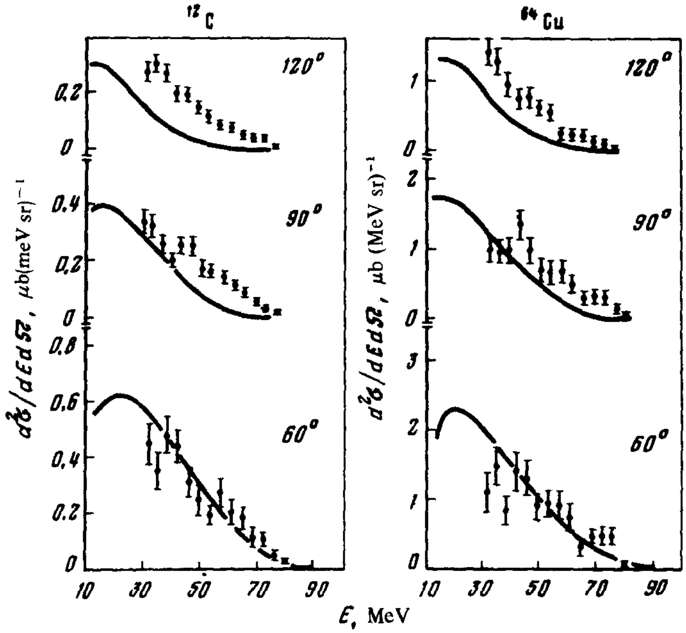

FIG. 1. A comparison of the theoretical curves and experimental data for production of π^+ mesons by 240-MeV protons in carbon and copper nuclei.

measurement data, we took into account the corrections for pion decay, for the additional energy release from the muon produced in the pion decay in the detector, and for the inelastic nuclear interaction of the pion with a detector material. The proton beam was monitored by recording with a scintillation telescope the proton scattered in a counter in the beam. The system was calibrated at a reduced intensity and by the activation method using the $^{12}C(p,pn)\,^{11}C(\beta^+)$ reaction in polystyrene by recording the positrons by using the β-γ coincidence method. The measurement accuracy of the proton flux was about 10%. A more complete description of the experiment will be published later.

The results of the measurements of the inclusive π^+ meson spectra at proton energies of 240 ± 6 MeV are shown in Fig. 1. We also measured the energy dependence of the differential cross section of pion production in copper (for pion energies greater than 30 MeV) in the 240 to 500-MeV energy range (Fig. 2). The smooth shape of the curve indicates that there are no resonance excitations with a width of a few tens of MeV. However, it would be interesting to perform measurements with a higher energy resolution and with a larger number of energy points.

In the theoretical analysis the nucleus was described by using a model of a degenerate Fermi gas with a density $\rho(r)$ in the Wood–Saxon form. The wave functions of the incident proton and pion were used in the eikonal approximation. For the optical proton-nucleus potential we used the expression

$$U_p(r) = V_p(r) + iW_p(r), \qquad V_p(r) = \epsilon_F(r) + B, \tag{1}$$

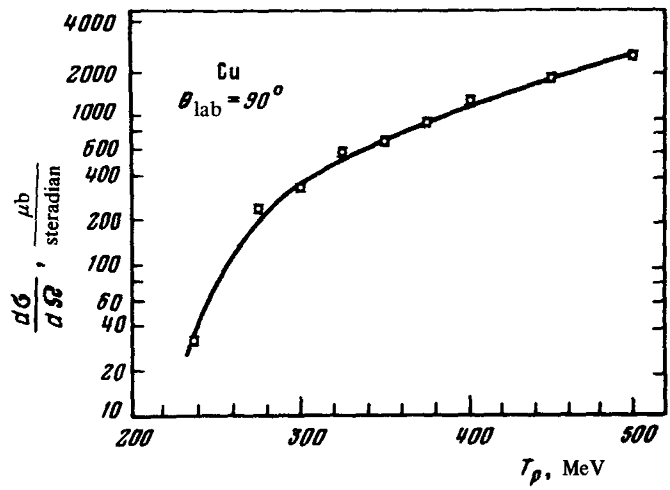

FIG. 2. Energy dependence of the differential cross section of pion production in copper at an angle of 90°. The solid curve is drawn through the experimental points.

$$W_p(r) = -\frac{p}{2m}\rho(r)\sigma_t\left[1 - \frac{7}{5}\frac{\epsilon_F(r)}{\epsilon_F(r) + E_p + B}\right], \tag{2}$$

where m, p, and E_p are the mass, momentum, and kinetic energy of the incident proton, B and $\epsilon_F(r)$ are the binding energy and Fermi energy of the nucleus, and σ_t is the average total cross section of the interaction of a proton with a nucleon of the nucleus.

The pion-nuclear optical potential was taken in the form $V(r) = q(r) - \nabla\alpha(r)\nabla$. The parameters of the potential were determined from the known phases of pion-nucleon scattering with allowance for the second-order effects.[7] The potential of a uniformly charged sphere $V_c(r)$ was used to describe the Coulomb interaction. Since the pair absorption[8] at energy $T_\pi \lesssim 70$ MeV is the major contribution to the imaginary part of the potential, we disregarded the pion rescattering.

The amplitude of pion production in the nucleus was expressed in the impulse approximation in terms of the T matrix on a massive surface for the vacuum subprocesses $pN \to NN\pi^+$, $pp \to d\pi^+$. The elements of the T matrix of the reactions, which were assumed to be constant (this is consistent with the experiment in the region near the threshold), were determined by analyzing the experimental data by the least-squares method.[9] In addition, the interference of the pion wave from different points of the nucleus was disregarded. Thus, the cross section for production of pions in the nucleus can be obtained in the following form:

$$\frac{d^2\sigma}{dE\,d\Omega} = \int d\mathbf{r}\,\rho(r)\left[1 - \frac{7}{5}\frac{\epsilon_F(r)}{\epsilon_F(r) + E_p + B}\right]\exp\left\{\int_0^\infty dz\left[\frac{2m}{p}W_p\left(\mathbf{r} - \frac{\mathbf{p}}{p}z\right)\right.\right.$$

$$+ \frac{1}{k}\,\mathrm{Im}\,v_k\left(\mathbf{r} + \frac{\mathbf{k}}{k}z\right)\Bigg]\Bigg\}\,\overline{d^2\sigma(r)/dE\,d\Omega}\,, \tag{3}$$

$$v_k(r) = \frac{2EV_o(r) - V_c^2(r) + k^2 a(r) + q(r)}{1 + a(r)}\,. \tag{4}$$

Here k and E are the pion momentum and energy, $\overline{d^2\sigma(r)/dE\,d\Omega}$ is the cross section for pion production in intranuclear nucleons, averaged over their momentum distribution at the point r. The corresponding equations are given elsewhere.[9]

A comparison of the results of a calculation and the experimental data is shown in Fig. 1. We can see a qualitative agreement for the two elements at angles of 60 and 90° and a discrepancy at an angle of 120°, which apparently is attributable to the unaccounted for nucleon correlations in the nuclei and pion rescattering and to the approximate nature of the used model. On the whole, the obtained results indicate that the inclusive cross section for production of pions in nuclei at proton energies below the production threshold in a free nucleon can be satisfactorily described within the context of a simple model for momentum distribution of nucleons in the nucleus.

The authors thank V. P. Dzhelepov and V. M. Lobashev for their interest in this work.

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