The experiment of Niiler *et al.*[5] was set up as follows: two protons were detected in coincidence and the energy spectrum of one proton was measured for a fixed energy of the other. The energy spectrum was then converted to the reaction cross section. The existence of the 6.7-MeV peak in the photon spectrum from the (γ, γ') reaction may indicate a contribution of the quasi-free scattering mechanism in formation of the products of the photodisintegration of ^{7}Li.

At an energy 8.5 ± 0.1 MeV in the scattered-photon energy spectrum a peak is observed which corresponds to the total binding energy of tritium (8.47 MeV), while at the energy corresponding to the total binding energy of ^{3}He (7.71 MeV) there is no peak (see Fig. 3). This result agrees with the data of Ref. 9, in which the contribution of various channels of photodisintegration of lithium to the total photoabsorption cross section was studied. In that work it was established that the yield of the reaction ^{7}Li$(\gamma, ^3$He) is negligible. Therefore a peak at energy 5.49 MeV equal to the binding energy of a nucleon in ^{3}He is not observed in the photon spectrum (see Fig. 2).

Thus, in the present work we have experimentally observed peaks in the photon-energy spectrum from the (γ, γ') reaction which permit us to deduce the reaction mechanism. The existence of a peak with energy 8.5 ± 0.1 MeV may indicate that inside the ^{7}Li nucleus before emission of a triton there is a formation of a ^{3}H cluster from quasifree nucleons. Proceeding from the width of the corresponding γ line we can, as in Ref. 1, estimate the time duration of formation of the ^{3}H nucleus: the width of the 8.5-MeV γ line is 150 keV, which corresponds to a process duration $\sim 10^{-21}$ sec. Similar peaks in the photon spectrum should accompany any reaction in which formation of a particle occurs before its emission from the nucleus.

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Production of π^+ mesons in collisions of low-energy protons with C and Cu nuclei

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Differential and doubly differential cross sections for production of positive pions by 240-MeV protons have been measured for the nuclei C and Cu. The energy dependence of the differential cross section for Cu is obtained at an angle 90° in the proton-energy range 240–500 MeV.

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INTRODUCTION

Study of pion production in collisions of nucleons with nuclei is an important source of information on the mechanism of the pion-nucleus interaction and on nuclear structure. The region of energies of the incident nucleons below the threshold energy for production of pions in collisions of free nucleons (~290 MeV) is especially interesting as a result of the fact that here the production of a pion is due entirely to nuclear effects. In this region of energies the role of absorption and scattering of the pions produced inside the nucleus is small and consequently the production process is more sensitive to the details of the internal structure of the nucleus.

At the present time the production of pions in nuclei has been well studied at energies above 400 MeV. A large quantity of experimental data on the inclusive production of charged and neutral pions in collisions of protons and neutrons with nuclei at energies 600–700 MeV was obtained in the fifties and sixties in the JINR synchrocyclotron at Dubna.[1–4] The production of charged pions of both signs by protons in many nuclei was measured at energies 400–500 MeV,[5] 580 MeV,[6] 585 MeV,[7] and 730 MeV.[8] This energy interval is characterized by energy distributions of the produced pions with broad maxima and with cross sections at the maximum of the spectra of several tens or hundreds of μb/MeV · sr. The experimental data agree qualitatively with the simple semiclassical model in which in the impulse approximation the production of pions is discussed in individual nucleons of the nucleus with a dominant contribution of the isobar mechanism and inclusion of the effects of absorption and scattering (including charge exchange) of pions in the nucleus.[9]

In recent years the intense investigation has begun of coherent production of pions in nuclei, i. e., production for fixed final states of the residual nucleus. These studies have been carried out for proton energies below 200 MeV, mainly in the accelerators at Uppsala[10] and Saclay.[11] With the coming on stream of meson factories, studies have appeared on coherent production at proton energies 600–700 MeV.[12,13]

As a consequence of the large momentum transfer the cross section for production should be sensitive to the properties of the nucleus at small distances. However, up to this time the theoretical description has not permitted reliable extraction from the experimental data of the form factor at high momenta. The experimental study of coherent production is hindered as a result of the small cross section for the process, which amounts to ~100 nb/sr for π^+ mesons and substantially less for π^- mesons. In the theoretical calculations it is necessary to take into account the contribution of multistep processes. A number of elementary processes necessary for the understanding of coherent production can be studied in the investigation of the inclusive production spectra. It should also be noted that, while in the coherent production reaction the nucleus remains in the ground state or a weakly excited state, the inclusive spectra are due mainly to high-energy excitations.

In the incident-proton energy interval 200–300 MeV at the present time there are no data either on coherent or inclusive production of pions. At these energies definite advantages arise as the result of the possibility of introducing rather well justified simplifying assumptions in the theoretical calculations.[14]

In the present work we have measured the inclusive doubly differential cross sections for production of π^+ mesons in collisions of protons of energy ~240 MeV with carbon and copper nuclei at three angles: 60, 90, and 120°.

At 90° we measured the experimental dependence of the differential cross section for pion production in copper in the energy range 240–500 MeV. Interest in study of the excitation function in this energy region is due to the possible appearance of features associated with the proposed formation of the Δ_{33} isobar in a bound state in the nucleus at proton energies ~300 MeV and of a dibaryon state at an energy 370 MeV, the existence of which remains problematical at this time. Since it is difficult to make convincing predictions regarding the widths of these states at the present time, it is desirable to measure the excitation function over a wide range of energies.

The measurements of the pion yield at a proton energy ~250 MeV also pursued practical aims: determination of the possible intensities of low-energy pion beams and their spectral composition with production of the pions in high-current accelerators with energy lower than the presently operating meson factories.

EXPERIMENTAL APPARATUS

The measurements were carried out in the proton beam of the JINR synchrocyclotron. A time-of-flight scintillation spectrometer[15] and a pion total-absorption spectrometer[16] developed at the Laboratory of Nuclear Problems, JINR, jointly with the Nuclear Research Institute, USSR Academy of Sciences, in the "Pion" program were used to record the pions. The characteristics of these detectors permit recording and spectrometry of π^+ mesons with energies up to 100 MeV, i. e., in a range which covers the energies of the generated pions.

A diagram of the experiment is given in Fig. 1. The external proton beam of the synchrocyclotron with energy 650 MeV was slowed down by means of carbon absorbers and then passed through a clearing magnet, a steel collimator in a 4-meter concrete wall, focusing lenses, and then onto the target.

The energy of the incident protons was established by selection of the thickness of the carbon absorbers. The average value and spread of the proton energies were determined by measurement of the range curve with a scintillation telescope. The average proton energy in the center of the target was chosen as 240 MeV. Here the total width of the spectrum at half-height was 12 MeV.

To measure the absolute number of protons incident on the target we used the method of measuring the scattered beam[6] by means of a scintillation telescope (Fig. 1). It was shown experimentally that for the given proton energies, type of target, and scattering angle the conversion coefficient relating the number of incident and scattered protons does not depend on the intensity of the direct beam.

To determine the conversion coefficient we used three methods: monitoring the direct beam at reduced intensities, activation analysis, and measurement of the number of tracks from fission fragments in interaction of beam protons with a lead target.

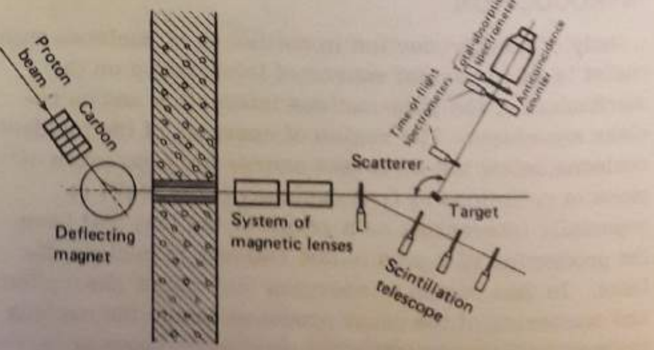

FIG. 1. Block diagram of experiment.

The errors in determination of the conversion coefficient in each of these methods was estimated as 10%. To obtain the absolute number of protons hitting the target under working conditions, the conversion coefficients obtained by the three methods were averaged.

The intensity of the proton beam at the target in the working measurements was ~3×10^8 sec^{-1}. Measurements were made for targets of area 3×3 cm^2 of copper and carbon of respective thickness 1.73 and 1.64 g/cm^2.

Pions produced in the target were recorded by a system consisting of a scintillation time-of-flight spectrometer and a total-absorption spectrometer—the π^+ detector—placed successively. The detector system was mounted on a rigid frame which could be rotated around a fixed target. The range of possible measurement angles was 15–140°. The size of the first counter of the time-of-flight spectrometer was $4\times4\times0.3$ cm, and the second counter $8\times8\times0.5$ cm. The flight path between the time-of-flight counters could be varied. In the experiments being described it was set at 100 cm. The counters were viewed by XP-1020 photomultipliers: the first counter by one multiplier, and the second by two multipliers for compensation of the time spread due to the finite time of passage of the light through the scintillator. The resolving time of the time-of-flight spectrometer was 500 psec.

In the total-absorption spectrometer we used a cylindrical plastic scintillator of polystyrene. The diameter was 180 mm and the length 250 mm. The ranges of pions with energies up to 100 MeV and protons with energies up to 200 MeV fall within this length. The energy resolution of the total-absorption spectrometer for pions in the energy interval studied was 1.5–2 MeV. The signal integration time in the total-absorption spectrometer was set equal to 100 nsec. With this integration time ~98% of π^+ mesons stopped in the detector decay with emission of a monochromatic muon which makes a constant addition of 4.1 MeV to the energy dissipation. In front of the total-absorption spectrometer was placed an anticoincidence counter with an opening 80 mm in diameter to exclude particles whose trajectories could leave the detector through the side walls. The characteristics of the time-of-flight spectrometer and the total-absorption spectrometer were studied in calibration measurements in pion and proton beams. For various energies of pions and protons the light yields and resolutions of the two spectrometers were measured.

Signals from all detectors were fed to electronic recording circuits and then to an HP-2116C computer. Information on the time-of-flight of a particle in the time-of-flight spectrometer and on the energy dissipation in the total-absorption spectrometer were stored in the computer in the form of two-dimensional time-of-flight–energy distributions and then recorded on magnetic tape. The measured distributions were displayed on a screen for preliminary rapid processing of the information and selection of the modes of operation of the spectrometer circuits. The boundary of the region of the two-dimensional distribution corresponding to pions was chosen from the calibration functions obtained for the two spectrometers with allowance for their resolutions.

The projections on the time and energy axes of the regions of the two-dimensional distributions corresponding to pions give the time-of-flight and energy spectra of the pions. From the two projections it is possible to obtain the energy distribution of the pions produced in the target. Comparison of the results of distributions established by the two methods is an additional criterion of correctness of the calibration and of the technique as a whole.

As control measurements and to test the possibilities of the method we made measurements of the yields of pions and protons at an angle 120° from a copper target at an incident-proton energy 620 MeV with an absolute accuracy ~15%. The value obtained for the differential cross section for production of pions with energies above 70 MeV, $d\sigma/d\Omega=3.7$ mb/sr, is close to the value from Ref. 17, from which for a proton energy 640 MeV and an angle 140° it is possible to estimate the cross section $d\sigma/d\Omega=4.8$ mb/sr. The measured yield of π^+ mesons $d\sigma/d\Omega=5$ mb/sr is more than twice the value from Ref. 6 at 580 MeV and agrees with the results of the latest measurements at 585 MeV.[7]

RESULTS

In Figs. 2 and 3 we have shown doubly differential cross sections for production of pions by 240-MeV protons in the nuclei C and Cu at angles 60, 90, and 120°, obtained from the experimental spectra in the pion total-absorption spectrometer. In Table I we have given the angular dependence (on the basis of the three angles of the measurements) of the differential cross sections integrated over energy ($T_p=240$ MeV). In Fig. 4 and in Table II we have shown the energy dependence of the differential cross sections for production of pions at 90° in the Cu nucleus, measured in the energy range 240–500 MeV.

As a lower boundary of the measured spectra we selected the energy 30 MeV (Figs. 2 and 3). The differential cross sections integrated over energy in Fig. 4

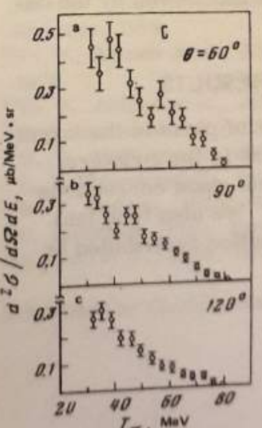

FIG. 2. Spectrum of doubly differential cross sections for production of pions by 240-MeV protons in carbon nuclei at angles 60° (a), 90° (b), and 120° (c).

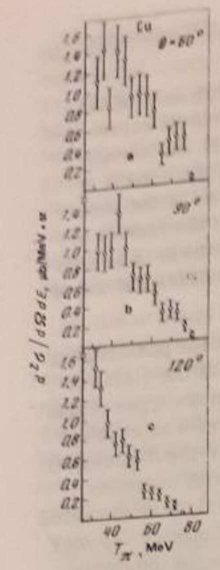

FIG. 3. The same as Fig. 2 but for Cu.

also correspond to the pion energy region above 30 MeV. The choice of the lower limit was due mainly to the fact that at energies below 30 MeV the pion spectra are distorted as the result of the spread in energy loss in the target. In measurement of the energy dependence (Fig. 4) at proton energies above 400 MeV the part of the pion spectra on the high energy end also was distorted as a result of the fact that the ranges of the pions exceeded the size of the total-absorption spectrometer. However, this fact did not affect the values of the differential cross sections integrated over energy.

In the figures we have shown the statistical errors of the measurements. In comparison of the absolute cross sections it is necessary, as was pointed out above, to take into account an additional 10% error associated with monitoring of the proton beam.

The experimental results are corrected for the background, which was measured in the absence of the target. It amounted to ~3% of the effect from carbon and ~1% of the effect from copper. The background is due to pions produced in the volume of air viewed by the detecting system.

ANALYSIS OF EXPERIMENTAL RESULTS

In calculating the energy spectra of pions in the target we took into account the energy loss in the counters, the air, and in the target itself, and made corrections for decay and multiple scattering. We also took into account the constant energy dissipation contributed by the muon from decay of the pion.

TABLE I.

deg.	dσ/dΩ, μb/sr	
	C	Cu
60	12.0±0.6	41.6±2.6
90	8.2±0.3	32.0±1.8
120	6.2±0.3	26.6±1.4

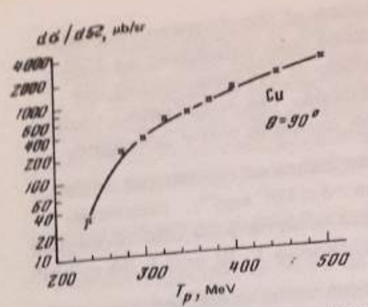

FIG. 4. Energy dependence of the combined differential cross sections for production of π^+ and π^- mesons at 90° in Cu. The curve was drawn through the experimental points.

The ionization loss was calculated with a program described in Ref. 18. To calculate corrections for multiple scattering and also for calculation of the effective solid angle, we used the program of Ref. 19. In calculation of the solid angle we estimated the effect of alignment on the value of the aperture. The errors due to alignment amounted to less than 2%.

An estimate was made of the effect on the shape of the pion energy spectra and on the value of the differential cross sections from the following physical processes: 1) inelastic interaction of pions with protons in the total-absorption spectrometer, 2) the consecutive $\pi^+ \to \mu^+ \to e^+$ decay, and 3) production of π^- mesons.

1) As the result of the inelastic interaction of pions in the scintillator of the total-absorption spectrometer the pion energy spectra are shifted toward lower energies. However, the cross section for inelastic interaction for most parts of the investigated pion spectra did not exceed several percent. Thus, the contribution of inelastic processes at an energy 20 MeV (30 MeV in the target) amounts to 1%, for 50 MeV ~3%, and for 80 MeV ~12%. Therefore for the given experimental accuracy of the spectra the influence of this factor will be insignificant.

The contribution of inelastic interaction of protons was estimated by the Monte Carlo method with use of data in the literature on (p, pn) reactions in carbon, the neutron interaction cross sections, and the recoil proton spectra in the nuclei of the detector. For measurements at angles beginning with 60°, the results of which are given in the present work, the admixture of protons in the region of the pion spectra with energies above 20 MeV can be neglected.

2) For the selected integration time of the signal in the total-absorption spectrometer, which was 100 nsec, on the average in 3.5% of the cases the μ^+ meson from decay of the π^+ meson in turn decays with emission of a positron with a definite energy release. Calculations

TABLE II.

T_p, MeV	dσ/dΩ, μb/sr	T_p, MeV	dσ/dΩ, μb/sr
237	32.0±1,8	375	914±25
275	234±10	400	1283±65
300	325±11	450	1808±68
325	576±15	500	2505±77
350	689±21		

showed that in half of the cases such events go outside the pion region in the two-dimensional distribution. A correction of ~2% was made to the measured results as a result of this effect.

3) In the energy spectra the contribution of π^- mesons leads mainly to a shift of the spectra toward higher energies as the result of the additional energy release in the nuclear capture of the stopped π^- meson. An approximate estimate of the admixture of π^- mesons can be made by using existing data at other energies. At an angle 90° in the ^{12}C nucleus at an incident-proton energy 185 MeV a ratio of the yields of π^+ mesons and π^- mesons was found in Ref. 10 to be ~45. At a proton energy 350 MeV the same ratio is ~11.[20] Consequently we can expect that the admixture of π^- mesons in the data presented in the present work for a proton energy 240 MeV does not exceed 4–5%. In the yields of pions at higher energies the contribution of π^- mesons will increase. Thus, at energy 450 MeV the ratio of the yields of π^+ and π^- mesons in carbon at 90° amounts to 7.2.[21] Therefore the energy dependence in Fig. 4 reflects the dependence of the combined yield of π^+ and π^- mesons.

DISCUSSION OF RESULTS

The cross sections obtained for production of pions in nuclei and the inclusive spectra of low-energy pions represent the first experimental data at proton energies below 350 MeV. The theoretical description of the pion-production process in nuclei in this energy region differs considerably from that at energies 600–700 MeV, where a large contribution is made by isobar production.[9] Qualitative agreement is observed with the results of calculations of near-threshold production of pions by protons at 250 MeV.[13] A more detailed comparison of theoretical calculations with the experimental data will permit study of the question of applicability of the impulse approximation which we have used and also determination of the relative contribution of production with formation of deuterons and free nucleons. We note that the simultaneous description of coherent-production processes with excitation of isolated states of nuclei in the final state,[10-13] including the use of polarized protons,[22] may possibly permit a clearer discussion of a number of the problems of the pion-nucleus interaction.

The absence of appreciable irregularities in the energy dependence of the cross section apparently indicates a small contribution of processes with production of baryon states or with production of isobar configurations. Therefore in view of the smallness of the possible effects it is desirable to carry out measurements with higher accuracy and with a larger number of points in energy.

We note the rapid dependence of the differential cross sections on energy for proton energies up to 300 MeV, which must be taken into account in planning economical high-current accelerators for practical use of pion beams. Comparison with data on the production of π^+ mesons at an energy 585 MeV (Ref. 7) shows that the differential cross section at 250 MeV is less by about 80 times. The magnitude of the doubly differential cross section at a pion energy 30–40 MeV amounts to ~5% of the corresponding cross section at proton energies ~600 MeV.

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