ground of 2 pulses/min) decaying with a half-life of 7 to 8 hrs. This small effect, which represents a cross section $\sim 10^{-33}\,cm^2$, did not enable us to determine the source of the activity, as thorium impurity amounting to $5 \times 10^{-6}\,\%$ could result in the same activity. Despite special purification of the gold, thorium impurity to this extent cannot be excluded. Thus the sought reaction of carbon capture (in our case C^{14} and heavier isotopes) lies at the limit of observation and cannot be established with certainty at the bombarding energies which were used.

A similar result was obtained in our investigation of the production of iodine from silver (carbon capture) bombarded by 480-Mev protons. In this instance also the small iodine yield (16 pulses/min, representing $\sigma \approx 5 \times 10^{-33}$) did not permit us to establish its production unambiguously as the result of the sought reaction.

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ENERGY SPECTRUM AND ANGULAR DISTRIBUTION OF π^+ MESONS, PRODUCED IN PROTON-PROTON COLLISIONS AT 660-670 Mev

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The energy spectrum of π^+ mesons produced in $p-p$ collisions by 670 Mev protons were measured for observation angles 19°30′, 38°, and 56°. It was found that, in the c.m.s., the shape of the π^+-meson spectrum for the $pp \rightarrow pn\pi^+$ reaction depends on the emission angle. The angular distribution of π^+ mesons produced in 660-Mev $p-p$ collisions is given, in the c.m.s., by Eq. (1). The value found for the total cross-section is $(14.4 \pm 1.2) \times 10^{-27}\,cm^2$.

1. INTRODUCTION

THE energy spectrum and the absolute yield of π^+ mesons, produced in $p-p$ collisions at 660 Mev, were first measured by Sidorov[1] in emulsions, at five values of the observation angle from 60° to 120°. Meshcheriakov et al.[2] studied the relative spectrum of π^+ mesons at 24° by means of magnetic analysis. Meshkovskii et al.[3] measured the absolute yield of π^+ mesons at 29°, 46°, and 65°

by means of a π^+ meson magnetic spectrometer. In the present work, the spectrum was measured at 29° and 46°. Finally, Neganov and Savchenko[4] measured the energy spectrum of π^+ mesons at four angles between 108° and 160°, and determined the absolute yield at eight angles between 60° and 160°.

The results of the above experiments can essentially be summarized as follows: First, it has been found[1,3] that the shape of the energy spectrum of the π^+ mesons produced in the $pp \to pn\pi^+$ reaction depends, in the c.m.s. of the two colliding nucleons, on the angle of emission of the π^+ mesons. Second, the angular distribution of π^+ mesons in the $pp \to pn\pi^+$ reaction can be described by the expression $a + b\cos^2\vartheta^*$, where ϑ^* is the emission angle in the c.m.s.[1,4]

Since the shape of the π^+-meson spectrum varies with the angle in the c.m.s., it is interesting to study this variation for the $pp \to pp\pi^+$ reaction. The above mentioned experiments are not, however, sufficient for that purpose. The degree of accuracy of some of the measurements of reference 1 makes it impossible to find the shape of the spectrum at certain angles. In reference 4 the spectrum was investigated only for the upper half of the total energy range in the c.m.s. The results of these experiments concerning the angular distribution of π^+ mesons are not consistent. While the angular distribution of π^+ mesons in the $pp \to pn\pi^+$ reactions is almost isotropic according to reference 1, this is not the case for the distribution obtained in reference 4.

In the present work we measured the energy spectrum and differential cross-section $d\sigma/d\Omega$ of π^+ mesons, produced at 19°30′, 38°, and 56°, in $p-p$ collisions at 670 Mev proton energy. This was done in continuation of earlier experiments,[3] in the course of which the spectrum was measured at 29° and 46°. The π^+ meson magnetic spectrometer, described in reference 3, was used in both experiments. The angle interval from 19°30′ to 56° in the laboratory system (l.s) corresponds to the interval from 35° to 90° in the c.m.s. The results of these experiments thus make is possible to study the angular dependence of the spectrum shape in the 35° to 90° interval in the c.m.s. (Sec. 5) from spectra obtained for five values of the angle. Measurements of the absolute yield of π^+ mesons at six values of the angle permitted us to calculate the corresponding angular distribution and to compare it with the results of other experiments (Secs. 3 and 4).

All measurements of the present work were carried out in the external proton beam of the synchrocyclotron of the Laboratory of Nuclear Problems, Joint Institute for Nuclear Studies.

2. EXPERIMENTAL RESULTS

Results of the measurements of differential cross-sections $d^2\sigma/d\Omega\, dE$ for the production of π^+ mesons in $p-p$ collisions at 670 Mev proton energy at three angles of observation are given in Table I. Only the statistical errors of the measurements are given in the table.

The energy spectra of π^+ mesons based on the data of Table I are given in Fig. 1. The curves are drawn for best fit with the experimental points. Figure 2 represents the spectra in the c.m.s. The

TABLE I

19°30′		38°		56°	
Meson energy Mev	$\frac{d^2\sigma}{d\Omega\, dE}\cdot 10^{29}$ cm² sterad⁻¹ Mev⁻¹	Meson energy Mev	$\frac{d^2\sigma}{d\Omega\, dE}\cdot 10^{29}$ cm² sterad⁻¹ Mev⁻¹	Meson energy Mev	$\frac{d^2\sigma}{d\Omega\, dE}\cdot 10^{29}$ cm² sterad⁻¹ Mev⁻¹
104	0.55±0.33	80	0.65±0.17	75	0.74±0.16
130	0.59±0.32	103	0.78±0.14	88	0.82±0.16
162	0.95±0.27	128	0.95±0.17	100	1.21±0.17
190	1.38±0.18	152	1.28±0.16	116	1.14±0.15
227	1.74±0.24	172	1.68±0.16	130	1.30±0.14
263	2.37±0.26	192	1.28±0.17	143	1.13±0.14
284	2.05±0.20	212	1.40±0.15	155	1.15±0.15
301	2.32±0.23	231	1.57±0.13	163	1.00±0.12
316	2.88±0.20	240	1.33±0.15	172	0.94±0.12
322	4.04±0.32	250	1.37±0.16	186	0.90±0.09
329	5.01±0.30	256	1.41±0.14	193	1.03±0.10
338	3.81±0.27	260	1.83±0.15	200	1.04±0.09
343	2.29±0.16	263	2.16±0.14	204	0.99±0.07
350	1.52±0.17	266	2.34±0.17	207	1.06±0.08
357	0.17±0.16	269	2.18±0.11	210	0.79±0.08
—	—	275	1.75±0.13	217	0.27±0.08
—	—	279	0.65±0.11	236	0.04±0.07
—	—	284	0.51±0.13	251	−0.04±0.08
—	—	295	0.26±0.11	—	—

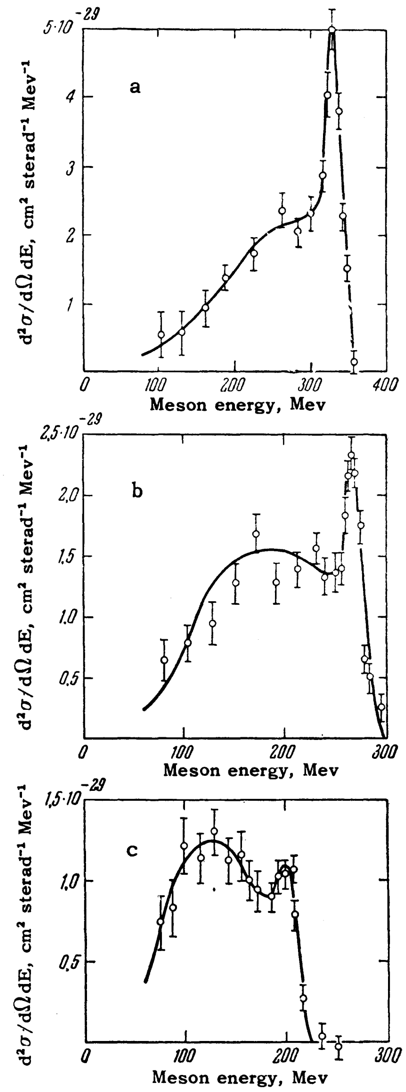

FIG. 1. Spectrum of π^+ mesons in laboratory system at emission angles: a – 19°30′, b – 38°, and c – 56°.

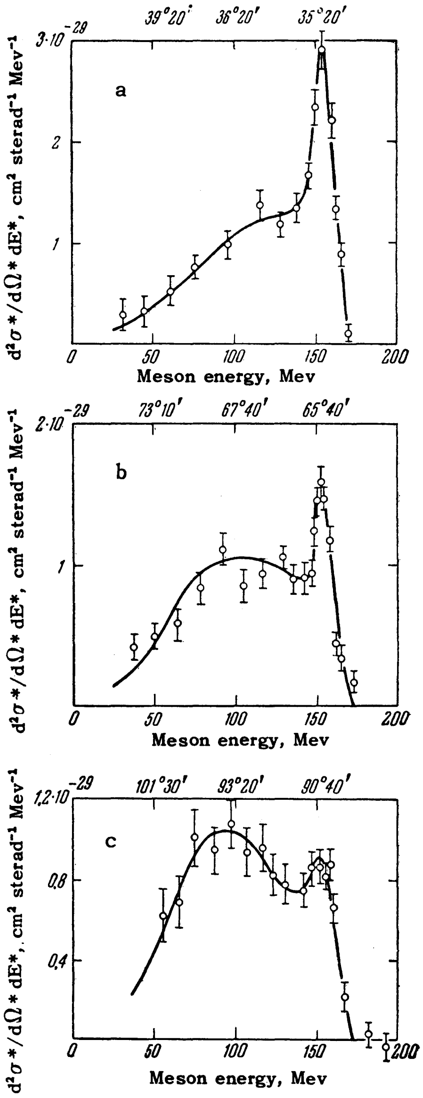

FIG. 2. Spectrum of π^+ mesons in c.m.s. at laboratory angles: a – 19°30′, b – 38°, and c – 56°.

values of the emission angle in the c.m.s. as a function of π^+ meson energy are indicated in the figure.

Results of the integration of the curves in Figs. 1 and 2, i.e., the cross sections $d\sigma/d\Omega$ in the l.s., and $d\sigma^*/d\Omega^*$ in the c.m.s., are given in Table II.

Systematic errors of the measurements, amounting to 10% for the angle 19°30′ and to 5% for the remaining angles, were taken into account, besides the statistical errors, in carrying out the integration. The tabulated values of the angle ϑ^* in the c.m.s. represent the angles of emission of π^+ mesons in the $pp \to d\pi^+$ reaction. The angles do not differ by more than 2° or 3° from the mean angles of emission of π^+ mesons in the c.m.s. for each spectrum.

TABLE II. Differential Cross-Sections at 670 Mev Proton Energy

Laboratory System		Center of Mass System	
ϑ	$d\sigma/d\Omega\cdot 10^{27}$ cm² sterad⁻¹	ϑ^*	$d\sigma/d\Omega\cdot 10^{27}$ cm² sterad⁻¹
19°30′	4.47±0.56	35°	1.42±0.18
38°	2.78±0.19	65°	1.17±0.08
56°	1.57±0.12	90°	1.01±0.08

3. ANGULAR DISTRIBUTION OF π^+ MESONS IN THE C.M.S. AND TOTAL CROSS-SECTION

It has been shown above that the results of the present experiment were obtained for three angles of observation at 670 Mev proton energy, while our earlier data for the three remaining angles[3] were obtained at 660 Mev. For the calculation of the angular distribution of π^+ mesons it is necessary to reduce all results to one energy. It is con-

TABLE III. Differential Cross-Sections in C.M.S. at 660 Mev Proton Energy

ϑ^*	35°	51°	65°	77°	90°	101°
$d\sigma^*/d\Omega^* \cdot 10^{27}$ cm² sterad⁻¹	1.32 ± 0.17	1.07 ± 0.08	1.08 ± 0.08	1.06 ± 0.07	0.93 ± 0.07	0.99 ± 0.10

venient to do this for 660 Mev, since other experiments on angular distribution have been carried out for that energy.[1,4]

A reduction to another energy value can be made using the experimental dependence of the yield of the $pp \to pn\pi^+$ reaction on the maximum meson momentum p^*_{max} in the c.m.s.[4] This dependence can be approximated by a power function of p^*_{max} (references 4 and 7). The cross-section of the reaction $pp \to d\pi^+$ in the considered narrow energy range from 660 to 670 Mev may be assumed, with an accuracy sufficient for our purposes, to remain constant, as follows from the experimental data.[5]

Results of the reduction of the values of $d\sigma^*/d\Omega^*$, obtained in the present experiment, to 660 Mev are given in Table III. The table includes also the values of $d\sigma^*/d\Omega^*$ for the three angles which were obtained by us earlier.[3]

Assuming that the angular distribution of π^+ mesons produced in $p-p$ collisions can be expressed, in the c.m.s., as $a + b\cos^2\vartheta^*$, we can find the values of a and b from Table III by the method of least squares. As a result, we obtain the following angular distribution

$$d\sigma^*/d\Omega^* = [(0.97 \pm 0.06) + (0.50 \pm 0.21)\cos^2\vartheta^*]\cdot 10^{-27}\ \text{cm}^2\text{-sterad}^{-1}. \quad (1)$$

The angular distribution of π^+ mesons in the $pp \to d\pi^+$ reaction, according to the data of Meshcherakov and Neganov,[5] is

$$d\sigma^*(pp \to d\pi^+)/d\Omega^* = [(0.100 \pm 0.014) + (0.435 \pm 0.025)\cos^2\vartheta^*]\cdot 10^{-27}\ \text{cm}^2\text{-sterad}^{-1}. \quad (2)$$

Subtracting Eq. (2) from Eq. (1), we obtain the angular distribution of π^+ mesons in the $pp \to pm\pi^+$ reaction:

$$d\sigma^*(pp \to pn\pi^+)/d\Omega^* = [(0.87 \pm 0.06) + (0.07 \pm 0.21)\cos^2\vartheta^*]\cdot 10^{-27}\ \text{cm}^2\text{-sterad}^{-1}. \quad (3)$$

The angular distribution (1) permits us to calculate the total production cross section of π^+ mesons in $p-p$ collisions at 660 Mev. The result is $\sigma^{\pi^+}_{pp} = (14.4 \pm 1.2) \times 10^{-27}\,\text{cm}^2$, in good agreement with the value $\sigma^{\pi^+}_{pp} = (14.8 \pm 2.1) \times 10^{-27}\,\text{cm}^2$ obtained as the difference between the cross section for all inelastic processes, $\sigma_{pp} = (18.4 \pm 2.1) \times 10^{-27}\,\text{cm}^2$ (reference 6) and the production cross section of neutral π mesons $\sigma^{\pi^0}_{pp} = (3.6 \pm 0.2) \times 10^{-27}\,\text{cm}^2$.[7]

The cross-section for the $pp \to pn\pi^+$ reaction can be calculated subtracting from $\sigma^{\pi^+}_{pp}$ the value of $\sigma(pp \to d\pi^+) = (3.1 \pm 0.2) \times 10^{-27}\,\text{cm}^2$.[5] This gives $\sigma(pp \to pn\pi^+) = (11.3 \pm 1.2) \times 10^{-27}\,\text{cm}^2$.

4. COMPARISON OF THE MEASURED ANGULAR DISTRIBUTION WITH THE RESULTS OF OTHER EXPERIMENTS

The angular distribution of π^+ mesons in $p-p$ collisions at 660 Mev was first studied by Sidorov,[1] who found that:

$$d\sigma^*/d\Omega^* = (1.03 \pm 0.18) \times [1 + (0.1 \pm 0.2)\cos^2\vartheta^*]\cdot 10^{-27}\ \text{cm}^2\text{-sterad}^{-1}. \quad (4)$$

In order to compare the above distribution with our results, we write it in the form:

$$d\sigma^*/d\Omega^* \sim 1/3 + (0.03 \pm 0.06)\cos^2\vartheta^*. \quad (5)$$

We write the angular distribution (1) found in the present work in the same form:

$$d\sigma^*/d\Omega^* \sim 1/3 + (0.17 \pm 0.07)\cos^2\vartheta^*. \quad (6)$$

If the cross-section $d\sigma^*/d\Omega^*$ is proportional to $1/3 + \alpha\cos^2\vartheta^*$ then the factor α represents the ratio of the number of anisotropically-distributed π mesons to the number of isotropically-distributed ones. It follows from Eq. (6) that the distribution obtained by us is nearly isotropic, since $\alpha = 0.17$. This result is consistent with the assumption made above, according to which the process $pp \to \pi^+$ process is nearly isotropic in the c.m.s.[3]

The distributions (5) and (6) differ somewhat from each other. It is necessary to take into account, while considering this discrepancy, that (as shown earlier[4]) Sidorov's reduction of the data contains an error which can be amended. After recalculating, we obtained the following distribution based on the corrected data of Sidorov:

$$d\sigma^*/d\Omega^* \sim 1/3 + (0.15 \pm 0.08)\cos^2\vartheta^*, \quad (7)$$

which coincides with the distribution (6).

We shall compare now the angular distribution (6) with the results of Neganov and Savchenko.[4] These authors found that

$$d\sigma^* (pp \rightarrow pn\pi^+)/d\Omega^* = [(0.58 \pm 0.13) + (0.88 \pm 0.04) \cos^2\vartheta^*] \times 10^{-27} \text{ cm}^2\text{-sterad}^{-1}. \quad (8)$$

This above expression is considerably different from Eq. (3). Combining Eq. (8) with Eq. (2) we obtain the angular distribution of π^+ mesons in p — p collisions

$$d\sigma^*/d\Omega \sim 1/3 + (0.64 \pm 0.12) \cos^2 \vartheta^*, \quad (9)$$

Distribution (9) is more anisotropic than those given by Eqs. (6) and (7).

It is necessary to note, in considering the discrepancy, that the four c.m.s. π^+-meson spectra given in reference 4 have been measured only for energies larger than 70 or 80 Mev, the maximum energy in the spectra being 160 Mev. The shape of the spectrum and the value of the cross section remain therefore unknown over approximately a half of the spectrum. The authors overcame the difficulty by calculating a theoretical curve which corresponds to their results in a narrow region from 80 to 130 Mev. It is well known, however, that no theory can at present be expected to predict the results of experiments on π-meson production, and the above-mentioned agreement cannot serve as a criterion for the correctness of the curve

We think, therefore, that the spectra measured by Neganov and Savchenko cannot be used to calculate the cross-section $d\sigma^*/d\Omega^*$ in the 140° to 170° interval in which the spectrum was measured.

5. SHAPE OF THE π^+ MESON SPECTRUM IN THE C.M.S.

The gradual change of the shape of the π^+ meson spectrum in the c.m.s. with the angle of observation can be observed in Fig. 3, where the spectra measured in the present and in our earlier experiment[3] are shown together. The measurements of the present work have been reduced to 660 Mev by the method outlined in Sec. 3. The experimental points have been omitted for clarity. The dotted line represents a part of the π^+ meson spectrum measured in relative units by Meshcherakov et al.[2] at 24° in the l.s. The area of that spectrum has been normalized in the figure to the value of $d\sigma^*/d\Omega^*$ that follows from the angular distribution (1) measured in the course of the present experiment. It can be seen that the result of reference (2) is in a good agreement with our curves.

It can be seen from Fig. 3 that a marked shift of the maximum towards higher energies occurs in the $pp \rightarrow pn\pi^+$ reaction with decreasing angle. The maximum of spectrum 5 is obtained at about 90 Mev, while those of the spectra 1 and 2 occur at 120 to 130 Mev.

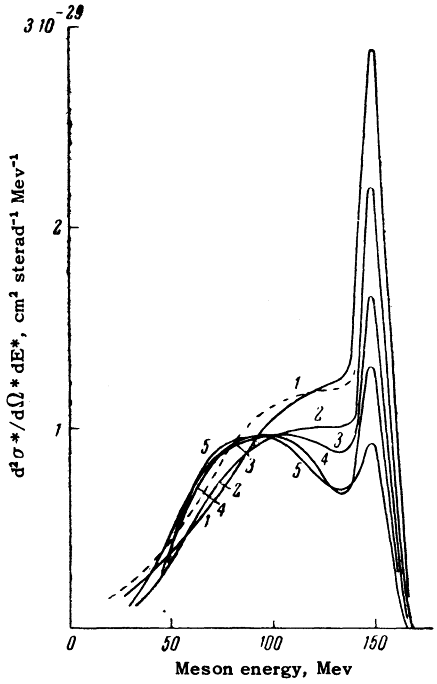

FIG. 3. Spectrum of π^+ mesons in c.m.s. at 660 Mev proton energy at the laboratory angles: 1 – 19°30, 2 – 29°, 3 – 38°, 4 – 46°, and 5 – 56°. The dotted line represents the measurements of Meshcheriakov et al.[2] at 24°.

All curves in Fig. 3 are close to each other in the region below 100 Mev, so that the π^+-meson spectrum does not depend strongly on the angle below 100 Mev. It follows from Fig. 3 that the angular distribution of π^+ mesons in that region is nearly isotropic. The fact that curves 1 and 2 lie below curves 3, 4, and 5 in the 50 to 100 Mev region means that, for a π^+-meson distribution of the type $a + b \cos \vartheta^*$, the factor b should be negative in that region. Such a conclusion, however, cannot be reached on the basis of our measurements since, up to 100 Mev, the curves in Fig. 3 coincide within the limits of experimental errors.

A marked change of the spectrum shape and anisotropy of the angular distribution takes place for π^+-meson energies above 100 Mev, as can be clearly seen in Fig. 3. The fraction of anisotropically distributed π^+ mesons systematically increases with increasing meson energy, from 7% in the 100 to 110 Mev range to 25% in the 120 to 130 Mev region. We cannot trace the change of the shape of the spectrum in the $pp \rightarrow pn\pi^+$ reaction for a further increase of the π^+-meson energy, since admixture of π^+ mesons from the

$pp \rightarrow d\pi^+$ reaction becomes probable in view of instrumental limitations.

In conclusion, the authors would like to thank V. P. Dzhelepov for his interest in their work and for making the synchrocyclotron available, and to K. A. Ter-Martirosian and I. M. Kobzarev for a discussion of the results.

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THE DECAY SCHEME OF Mo^{99}

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We have measured the angular correlation of the 742 — 180 kev cascade γ-rays emitted in the decay of Mo^{99}. By chemical separation of Tc^{99m} it was shown that the 1.23-Mev β-transition in Mo^{99} goes to the isomeric state in Tc^{99}, while $(7 \pm 1)\%$ of the 140 kev γ-quanta are not associated with the isomeric transition. In the discussion of the data, arguments are presented for assigning the quantum numbers $3/2^+$ to the ground state of Mo^{99}, $3/2^+$ or $5/2^+$ to the excited state of Tc^{99} at 922 kev and $7/2^+$ to the 180 kev state in Tc^{99}.

1. INTRODUCTION

THE radiation accompanying the decay of Mo^{99} has been investigated in many papers, in which the decay scheme of the isotope is also discussed. Study of the isomeric state of Tc^{99} which is produced in the decay of Mo^{99} has made it possible to assign with certainty the quantum numbers of the first two excited states of Tc^{99}, which have excitation energies of 140 and 142 kev.[1-3] A direct measurement gave $I = 9/2$ for the total angular momentum of the ground state.[4] The location of the levels in Tc^{99} at 180 and 922 kev has also been definitely established.[5-7] Different authors are in agreement on the branching ratio[1,5] for the two most intense β-transitions in Mo^{99} (with end points 0.445 and 1.23 Mev). The data of reference 8, in which a direct β-transition from Mo^{99} to the ground state of Tc^{99} was detected, are of interest. All the data enumerated above still do not enable us to make reliable assignments for various excited levels in Tc^{99} and for the ground state of Mo^{99}.

The excited state in Tc^{99} at 922 kev, which is produced in the β-decay with end point $E_\beta = 0.445$ Mev (Fig. 1), is the starting point of two γ-cascades: 742 — 180 kev and 742 — 40 — 140 kev.[7] We have measured the angular correlation for one of these cascades in order to make quantum assignments for the 180 and 922 kev levels in Tc^{99}. The results of these measurements will be presented later in the paper. We also shall consider the