MASS SPECTRUM OF CHARGED PARTICLES EMITTED IN THE ABSORPTION OF π^- MESONS BY PHOTOGRAPHIC EMULSION NUCLEI

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The yield and spectrum of charged particles produced in photographic emulsion nuclear disintegrations induced by slow and fast (300 MeV) π^- mesons are studied. The yields of deuterons and tritons with energies ≥ 10 MeV from light nuclei (C, N, O) disintegrated by slow π^- mesons (σ_π stars) are approximately 40 and 15%, respectively. The yield of deuterons with energies ≥ 20 MeV from heavy nuclei (Ag, Br) is close to 40% and is small for energies < 20 MeV. Absorption of fast π^- mesons does not result in appreciable emission of complex particles.

In the absorption of π^- mesons by emulsion nuclei (σ_π stars), about 15% of the emitted particles are singly charged and have energies ≥ 30 MeV.[1] Rabin et al.[2] have shown that about half of these fast particles are deuterons and tritons. This result cannot be reconciled with a thermodynamic picture of the disintegration. Estimates show that at an excitation energy of ≈ 140 MeV, which is the amount released in the absorption of a π^- meson, the number of fast nucleons can comprise in all only $\sim 0.5\%$ and the ratio N(d, t)/N(p) should not exceed ~ 0.2.

We can therefore assume that the disintegration products are the result of a special direct reaction in which the π^--meson energy is transferred to a small group of nucleons in the original nucleus.[3]

The present investigation is a continuation of our previously published work.[2] Our intention was to improve the data on the yield of various charged particles and to measure their spectra. The work was done using nuclear emulsions. The dimensions of a single emulsion layer were $100 \times 100 \times 0.4$ mm. The irradiation was carried out in the slow π^--meson beam of the JINR synchrocyclotron. For calibration purposes these same emulsions were irradiated by ≈ 120 MeV protons in such a way that they stopped in the center of the emulsion layer. In the work with fast π^- mesons we used emulsion layers irradiated in a 300 MeV π^--beam by V. M. Sidorov's group at JINR. Charged particle mass spectra were measured for light (C, N, O) and heavy (Ag, Br) emulsion nuclei. Separation of events in light and heavy nuclei was made using a criterion based on the Coulomb barrier and Auger electrons.[4]

1. ABSORPTION OF SLOW π^- MESONS

1. Yield of charged particles with energy $\lesssim 20$ MeV. Charged particle mass measurements in σ_π stars for residual ranges 0.2 mm $\leq$ R $<$ 1.0 mm were made by an ionization method in type K emulsion. For this type of emulsion the most sensitive ionization parameter is the mean length of a bunch. We have shown[5] that the mean length of a bunch is proportional to the energy of the particle up to ~ 20 MeV, independent of the particle mass.

We selected for measurement particle tracks located at a distance $100\,\mu \leq H \leq 300\,\mu$ from the surface of the undeveloped emulsion layer. The angle of inclination of the particle track to the plane of the emulsion did not exceed 10°. In all we selected 108 σ_π stars, 43 from light nuclei and 65 from heavy nuclei. To identify the charged particle we measured the mean bunch length at a residual range $R = 200\,\mu$. As an index of the track ionization we used the ratio x of the mean bunch lengths for a given particle and for the calibration protons. The values of x calculated from the range-energy relation for deuterons, tritons, and α particles are

$$x_d = 1.35, \qquad x_t = 1.61,$$
$$x_{\text{He}^3} = 3.57, \qquad x_{\text{He}^4} = 4.03.$$

The measured distribution of the values of x contains two groups of particles: $x < 2.0$ and $x \geq 2.0$. The latter group (consisting of 8 particles) can be assigned to doubly-charged particles. All of them have a residual range $R < 0.3$ mm. The fraction of the total number of charged particles represented by this group is

$\alpha(He^3, He^4) = 0.070 \pm 0{,}025.$

The particle group with x < 2.0 consists of the singly-charged particles p, d, t. The distribution of x for 83 particles with x < 2.0 is shown in Fig. 1, where the arrows indicate the values of x_p, x_d, x_t. The solid curve shows the shape of the proton line. The observed spectrum can be expressed in the form

$$y(x) = N\Sigma\alpha_k f_k(x), \qquad (1)$$

where x is the measured value of the ionization parameter, N is the total number of particles, α_k is the relative yield of particles of type k, $f_k(x)$ is the distribution function of the value of x for a particle of type k.

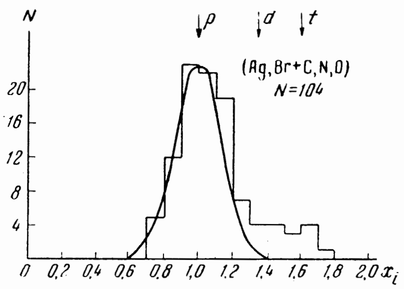

FIG. 1. Distribution of values of the ionization parameter for singly-charged particles emitted in the disintegration of emulsion nuclei.

We have shown that the distribution of x for protons at a residual range R = 200 μ is well described by a normal law with a relative dispersion σ = 0.134.[5] Values of α_k were determined from the spectrum of Fig. 1 by the method of moments. The results of these evaluations are listed in Table I, in the column R = 0.2–1.0 mm.

2. The secondary-particle energy interval ~ 20–100 MeV. Mass measurements of secondary particles with a residual range R ≥ 1.0 mm were made in type P emulsion by the method of multiple scattering. We selected altogether 1870 σ_π stars, 900 from light nuclei and 970 from heavy nuclei.

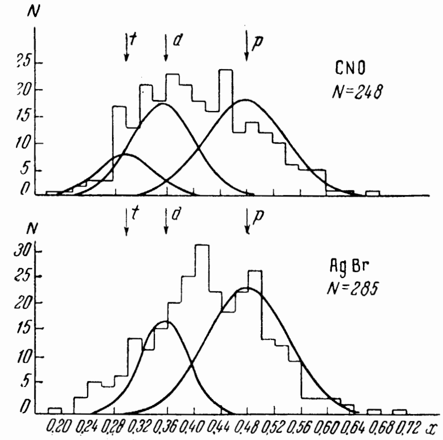

FIG. 2. Distribution of second differences for particles from σ_π stars.

Figure 2 shows the measured distribution of second differences x (in microns) for particles with residual ranges 2.5 mm ≤ R < 5.0 mm. In the residual range interval ≥ 1.0 mm only singly-charged particles are present in the spectrum. The observed spectrum can also be written in the form of Eq. (1), where f(x) is the distribution function of the scattering parameter. In Fig. 2 the solid curves show the functions for protons, deuterons, and tritons with the corresponding weights.

The distribution of second differences is described by a normal law with a dispersion σ_0 and a mean value $\bar{x}_k$. The dispersion σ_0 and the mean value $\bar{x}_p$ were found from scattering measurements on the tracks of the calibration protons. Figure 3 shows the results of measuring the proton line for residual ranges R = 1.0 mm and R ≥ 4.0 mm. The solid curves in Fig. 3 are normal distributions with a mean value $\bar{x}_p = 0.48\mu$ and a dispersion $\sigma_0 = 0.51\,\mu$. The yield of the different particles was determined from Eq. (1) by the method

Table I. Yield of p, d, and t in absorption of slow and fast (300 MeV) π^- mesons by light nuclei (C, N, O) and heavy nuclei (Ag, Br) in emulsion

		Absorption of slow π^- mesons				Absorption of fast π^- mesons, 300 MeV, R > 4.0
		R = 0.2 — 1.0 *	R = 1.0 — 2.5	R = 2.5 — 5.0	R ≥ 5.0	
C, N, O	p	0.60±0.07	0.44±0.01	0.49±0.01	0.49±0.02	
	d	d+t=0.40±0.07	0.42±0.01	0.37±0.01	0.31±0.02	
	t		0.14±0.01	0.14±0.02	0.20±0.04	
Ag, Br	p	0.84±0.08	0.51±0.01	0.61±0.01	0.59±0.01	
	d	0.14±0.02	0.49±0.01	0.39±0.01	0.26±0.02	
	t	0.02±0.06	0±0.02	0±0.02	0.15±0.03	
C,N,O+Ag,Br	p	0.75±0.02				0.96±0.12
	d	0.23±0.06				0.04±0.12
	t	0.02±0.06				0

*Residual range R in mm.

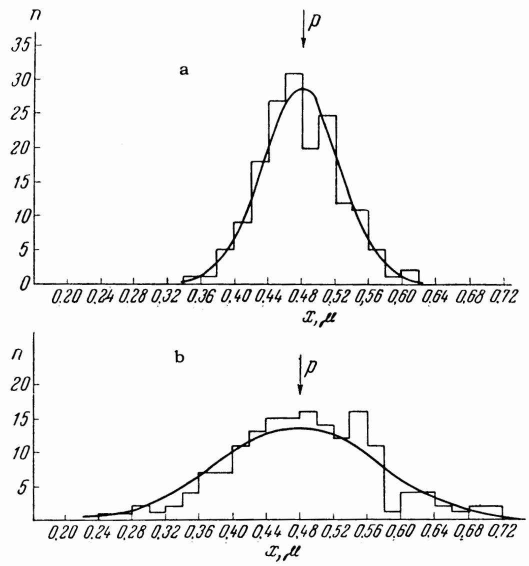

FIG. 3. Proton line, measured in tracks of calibration protons with a residual range R = 1.0 mm (a) and R ≥ 4.0 mm (b).

of least squares. The results are given in Table I for three residual range intervals.

3. Energy spectra of secondary charged particles. The multiple scattering measurements provide the possibility of determining energy spectra of the protons, deuterons, and tritons. It follows from Fig. 2 that particles with a second difference $x \geq 0.48\,\mu$ are mainly protons; for $x = 0.36-0.48\,\mu$ the particles are mainly protons and deuterons; and for $x < 0.36\,\mu$ only deuterons and tritons are present. The errors arising in such a classification do not exceed ~ 20% for residual ranges 1.0 mm ≤ R < 2.5 mm and amount to a total of ~ 4% for residual ranges R ≥ 5.0 mm. The deuteron and triton energy spectra can then be obtained from the range distributions of the particles N(R) for the stated intervals of x:

$$N_p(R) = N_1(R|x \geqslant 0.48\ \mu),$$
$$N_d(R) = N_2(R|0.36\ \mu \leqslant x < 0.48\ \mu) - N_p(R),$$
$$N_t(R) = N_3(R|x < 0,36\ \mu) - N_d(R). \qquad (2)$$

In plotting the spectra we introduced a correction for the effect of the plane emulsion chamber. The correction was calculated without taking into account multiple scattering. The particle energy distributions obtained in this way for light nuclei are given in Fig. 4, where the abscissa represents particle energy in MeV and the ordinate is the charged particle yield in arbitrary units. Only the statistical errors are shown.

2. ABSORPTION OF 300 MeV π^--MESONS

In measurements of the masses of the products of disintegration of nuclei by fast π^- mesons in

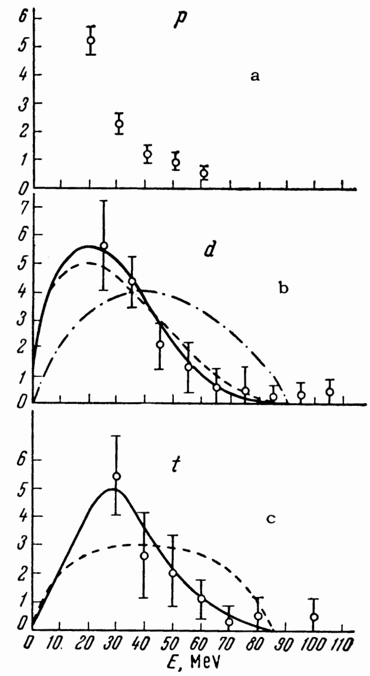

FIG. 4. Energy distribution of singly-charged particles emitted in the disintegration of light emulsion nuclei. The curves are the energy spectra corresponding to phase space (dashed curve) and to the pole particles He^3 (dot-dash curve) and He^4 (solid curve).

type R emulsion, we selected 83 interactions in which one of the prongs had a residual range ≥ 4.0 mm. We selected only the events in which there were no relativistic or gray prongs among the secondary particles. By this selection we greatly reduced the admixture of π^- meson–nucleus inelastic scattering events. It is impossible to separate cases of inelastic π^--meson scattering with charge exchange; these events amount to ~ 20%.[6] The average number of prongs for the selected stars is $\bar{\nu} = 3.5$.

Mass measurements were made with the constant-sagitta method. The result is shown in Fig. 5 where the abscissa represents the second difference x_μ and the ordinate the number of events. The fractions of protons and deuterons, calculated

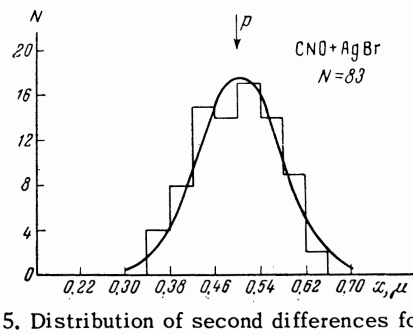

FIG. 5. Distribution of second differences for particles emitted in the disintegration of emulsion nuclei by fast π^--mesons.

from Eq. (1) by the method of moments, are

$$\alpha_p = 0.96 \pm 0.12. \qquad \alpha_d = 0.04 \pm 0.12.$$

The solid curve in Fig. 5 shows the proton line calculated for a mean value $\bar{x}_p = 0.50\,\mu$ and a dispersion $\sigma_0 = 0.70\,\mu$. The curve has been normalized to the total number of particles.

Thus, in the absorption of fast π^- mesons the number of deuterons emitted is small and does not exceed 10%.

3. DISCUSSION OF RESULTS

We wish to compare the results of our measurements with the theory of direct reactions proposed by I. S. Shapiro,[3] who considered data on the disintegration of light nuclei, principally C and O. The fraction of N nuclei in the emulsion amounts to about 10% and can be neglected.

According to the conception of direct nuclear reactions, the nucleus is a dynamic system which virtually emits and absorbs reversibly all kinds of particles. The incident π^- meson interacts with a virtual particle as with a free particle. This picture can be described with Feyman diagrams. The simplest of these is the pole diagram shown in Fig. 6.

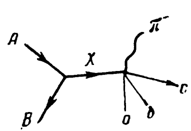

FIG. 6.

The nature of the outgoing particles is completely determined by the characteristics of the disintegration of the particle X which is virtually emitted by the nucleus A. The final state interaction leads to formation of a compound nucleus whose effect is easy to take into account. It is possible to choose the conditions so that the effect of the compound nucleus will be small. Then a comparison of the results of disintegration of complex nuclei and of the simplest nuclei, virtually emitted by a complex nucleus, allows us to establish what kind of virtual particles play an important role in π^--meson capture.

Let us consider the absorption of a pion by different virtual particles. Capture of a negative pion by a singly-charged pole particle (proton or deuteron) results in the emission of fast neutrons. In this case either neutron stars (so called ρ-stoppings) or evaporative σ stars are formed.

Experiments performed by Lederman and others with a diffusion cloud chamber[7] showed that in the disintegration of carbon nuclei by pions, charged particles are absent in 16% of the cases. According to the ideas discussed above, these cases can be considered as absorption of π^- mesons either by a single proton or by an (n, p) pair (see Table II).

The simplest nuclei in which capture can lead to appearance of direct charged particles are the proton pair (p, p) and the nuclei He^3 and He^4. Capture of a π^- meson by a (p, p) pair results in emission of two nucleons in opposite directions. The π^--meson energy is distributed equally between the nucleons. In absorption by a free pair, monoenergetic protons arise with an energy of about 60 MeV. However, the Fermi motion of the nucleons in a nucleus leads to a broad spectrum with a peak near 60 MeV and a width of about 40 MeV. Figure 4a shows the observed energy distribution of protons emitted in the disintegration of light nuclei. The spectrum is essentially cut off at about 60 MeV. We can conclude from this that the proton pair (p, p) is not important in the capture of a π^- meson.

For capture in the virtual nuclei He^3 and He^4, several particles arise in the final state and the picture of the disintegration becomes more complex. In the absorption of a π^- meson by the free nuclei, the following reactions are possible:

$$He^3 + \pi^- \to p + 2n, \qquad (3a)$$

$$\to d + n, \qquad (3b)$$

$$He^4 + \pi^- \to p + 3n, \qquad (4a)$$

$$\to d + 2n, \qquad (4b)$$

$$\to t + n. \qquad (4c)$$

Table II. Results of disintegration of light nuclei and α particles by slow π^- mesons

	Disintegration of C^{12}, O^{16} nuclei				Disintegration of He^4 nuclei[9]	
Type of disintegration	Absorption mechanism	Fraction of disintegrations of a given type	Emitted particles	Yield of different particles; $R \geqslant 1.0$ mm	Fraction of disintegrations of a given type	Yield of different particles
ρ-stoppings	Pole (p, d)	0.16	n		0.15 ± 0.02	
I. σ-stars	Pole (α)	0.65	p	0.46 ± 0.01		—
			d	0.39 ± 0.01		—
			t	0.15 ± 0.01		0.19 ± 0.02
II. σ-stars		0.19	p, d, t	—	—	—

In both cases channels exist which lead to emission of monoenergetic particles. In reaction (3b) deuterons are formed with an energy of about 40 MeV. The kinetic energy of the tritons emitted in the disintegration of helium is approximately 30 MeV. Only pion capture by helium nuclei has been studied experimentally.[8,9] The most accurate data have been obtained by Block et al.[9] in a helium bubble chamber. From the charged-particle range distributions the authors established that the yield of tritons was (19 ± 2)%. In pion capture by virtual He^3 and He^4, the Fermi motion results in a broad energy distribution with peaks near 40 and 30 MeV for deuterons and tritons.

The theoretical question of π^--meson absorption by complex nuclei has been considered by Shapiro and Kolybasov.[10] They computed the relative yields of different particles and their energy distributions in the disintegration of carbon nuclei. The calculations were carried out using the pole diagram. Figure 4b shows the measured and calculated deuteron energy distributions. The dot-dash curve is computed assuming the pole particle is a He^3 nucleus. Comparison with the experimental distribution shows that the He^3 nucleus is not important in π^--meson absorption.

The accuracy of the experimental points is not sufficient to distinguish between the distributions corresponding to phase space (dashed curve) and to a pole α particle (solid curve). Figure 4c shows the triton energy spectrum. In spite of rather large errors, the experimental spectrum indicates a pole α particle. Evidently π^--meson capture by a virtual α particle is the main source of fast particles. Then, knowing the total number of π^--meson captures and taking into account the ratio $N(d+t)/N(p) \approx 1$ (Table I), we find that about 65% of all disintegrations of C^{12} and O^{16} nuclei occur through capture of a negative pion by a virtual α particle (Table II).

The yield probabilities of different particles in the disintegration of C^{12} nuclei has been calculated only for π^--meson absorption by a virtual α particle. Shapiro and Kolybasov[10] showed that with good accuracy the following relation exists between the yield ratios of different particles in π^--meson capture by a carbon nucleus and a free α particle:

$$\lambda_X{}^C / \lambda_p{}^C \approx \lambda_X{}^\alpha / \lambda_p{}^\alpha, \qquad (5)$$

where λ_X^C is the emission probability of the particle X from the nucleus C. From this relation it follows that a similar equality exists also for the relative yields of the different particles:

$$\lambda_X{}^C / \Sigma\lambda_X{}^C = \lambda_X{}^\alpha / \Sigma\lambda_X{}^\alpha.$$

Table II lists values of the relative emission probabilities of protons, deuterons, and tritons in the disintegration of C^{12}, O^{16}, and α particles.[9] In the case of C^{12} and O^{16} nuclei, the data are for particles with a residual range $R \geq 1.0$ mm. It can be seen from Table II that the relative emission probabilities of tritons are nearly the same in the two cases. We can conclude from this that Eq. (5) is rather well satisfied, which argues in favor of the pole mechanism of pion absorption.

Experimental results on the disintegration of heavy nuclei (Ag, Br) show that among the secondary particles with a residual range $R \geq 1.0$ mm, about 40% deuterons are observed. The number of tritons is insignificant. For residual ranges 0.2 mm $\leq R < 1.0$ mm the deuteron yield drops to ~14%, close to the yield predicted by statistical calculations. The fraction of cases when charged particles are absent amounts to approximately 40%.

In the absorption of fast π^- mesons, the number of complex particles is small and within the experimental errors does not exceed ~10%. Comparison of the experimental results on the disintegration of light nuclei with calculations based on the theory of direct reactions shows that the experimental data are best described by the pole mechanism of π^--meson absorption by a nucleus if we assume that the virtual particle is a He^4 nucleus.

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185