SOVIET PHYSICS JETP VOLUME 24, NUMBER 6 JUNE, 1967

A STUDY OF PION CAPTURE BY He^2. *II. REACTIONS INVOLVING NUCLEAR DISINTEGRATION*

O. A. ZAĬMIDOROGA, M. M. KULYUKIN, R. M. SULYAEV, I. V. FALOMKIN, A. I. FILIPPOV, V. M. TSUPKO-SITNIKOV, and Yu. A. SHCHERBAKOV

Joint Institute for Nuclear Research

Submitted to JETP editor July 8, 1966

J. Exptl. Theoret. Phys. (U.S.S.R.) 51, 1646–1653 (December, 1966)

Pion capture by He^3, resulting in disintegration of the nucleus, is investigated with a high pressure diffusion chamber in a magnetic field. The relative probabilities of the processes and the momentum spectra of the secondary charged particles are measured. The results are compared with calculations based on the two-nucleon capture model.

INTRODUCTION

THE first part of the present work[1] was devoted to a study of charge exchange and radiative capture of negative pions by He^3, occurring without disintegration of the nucleus. These processes were separated by measuring the range of the tritium nucleus in the gas of a high-pressure diffusion chamber.

In addition to these processes, capture of pions by He^3 can be accompanied by the following processes, which lead to disintegration of the nucleus:

$$\pi^- + \mathrm{He}^3 \to p + n + n, \qquad (1)$$

$$\pi^- + \mathrm{He}^3 \to d + n, \qquad (2)$$

$$\pi^- + \mathrm{He}^3 \to d + n + \gamma, \qquad (3)$$

$$\pi^- + \mathrm{He}^3 \to p + n + n + \gamma. \qquad (4)$$

By measuring the probability ratio of different processes and investigating the spectra of secondary charged particles produced when stopped π^- mesons are captured by such a very simple nucleus such as He^3, we can obtain information on the main features of the pion absorption mechanism.

A theoretical investigation of the capture of pions by He^3 has been the subject of several papers. The calculations of Messiah[2] were made in the impulse approximation, with account taken of data on pion capture in deuterium and in hydrogen. The nuclear wave function used by him can presently not be regarded as suitable, since it does not yield the measured He^3 radius. Messiah obtained relations between different capture modes and the gamma-quantum spectrum in radiative processes.

Struminskiĭ[3] calculated the ratio of the charge-exchange and radiative-capture processes, using the experimental value of the Panofsky ratio in hydrogen; this eliminated the uncertainties connected with the use of perturbation theory in the calculations. On the basis of the theorem concerning the completeness of the system of wave functions, he calculated the relative probabilities of different radiative processes, and also the energy spectrum of the deuterons and gamma quanta in process (3), taking account of the interaction in the final state.

Divakaran[4] used as the basic hypothesis the two-nucleon mechanism of absorption of pions by He^3. The calculation was made with the aid of the matrix element of the inverse process—pion production near threshold in NN collision, as obtained by Eckstein[5] on the basis of an analysis of the experimental data. Divakaran used a wave function which had a Gaussian form and agreed with the experimental data on scattering of electrons by He^3 and H^3 nuclei. The nucleon correlation was taken into account in an interaction operator containing a delta function of the coordinates of the nucleon pair. He calculated the absolute and relative probabilities of the different capture modes, and also the proton spectrum in process (1).

The purpose of the present work was to measure the relative probabilities of reactions (1), (2), and (3) and to obtain the spectra of the protons and deuterons in processes (1) and (3).

To study the capture of negative pions in He^3, we used a high-pressure diffusion chamber in a magnetic field[6]. The experimental setup and the obtained experimental material were described in detail earlier[1]. The experimental data were obtained in three runs. In run I, the pions were stopped in the chamber at a pressure of 17.5 atm of He^3 in a magnetic field of 12,000 G. The data obtained in this run were used to separate processes (1), (2), and (3). In run II, the chamber, under pressure of 17.5 atm, was in a magnetic field of 6,000 G. This magnetic field was optimal for obtaining a large number of stopped pions in the chamber. The data of this run were used to increase the statistics of radiative-capture events in reaction (1). In run III, the chamber was filled with He^3 to a pressure 6.5 atm, and the magnetic field intensity was 12,000 G. The data of this exposure were used to a more thorough study of those processes in which low-energy reaction products were emitted.

All the events of pion capture by He^3 were single-prong stars. They could be easily identified by the characteristic change in curvature and by the ionization of the stopped pion. The secondary protons and deuterons, with momenta exceeding 120 MeV/c, were not stopped by the gas in the chamber. In particular, the deuteron momentum in process (2) is 414 MeV/c, and this case is represented in the chamber by a single-prong star whose secondary prong does not terminate in the chamber. Some capture events from reactions (1), (3), and (4) were identified as single-prong stars with secondary-particles terminating in the chamber (1 pt), and others as single-prong stars whose prongs did not terminate in the sensitive layer of the chamber (1 pn). In the 1 pn star group we measured the momenta of the secondary charged particles by determining the curvature of the track, and in the 1 pt group we measured the ranges. In addition, we measured the initial momentum and the range of the secondary particles along the 1 pt stars, in order to separate the protons and the deuterons. All the necessary measurements were made with a reprojector[7], with the aid of which we reconstructed the picture of the event in space. The efficiency of recording a track of given length was calculated in all cases by the Monte Carlo method, using the measured topography of the stopped mesons.

THE REACTION $\pi^- + He^3 \to d + n + \gamma$

In separating this reaction, we started from the fact that almost the entire energy released during the capture of the π^- meson by the He^3 is carried away by the gamma quantum. We could therefore hope to register the bulk of the events of this reaction among the 1 pt cases. To this end, we measured in the 1 pt star group of runs I and II the masses of the secondary particle. Measurements of the particle momenta were made by means of templates of variable curvature. In calculating the momenta we took into account the non-uniformity of the magnetic field relative to the height of the sensitive layer of the chamber. In measuring the mass we introduced the following selection criteria:

1) The angle between the secondary-particle track and the plane perpendicular to the direction of the magnetic field did not exceed 30°.

2) The range of the secondary particle was not less than 6 mg/cm^2 in run I, at a gas density 2.3 mg/cm^2, and less than 2 mg/cm^2 in run III, at a gas density 0.08 mg/cm^2.

In run I, the criterion 2) excluded cases when the pions were captured by He^3 with tritium in the final state. In run III, at low He^3 pressure, this criterion excluded only events with tritium from the charge-exchange reaction. On the other hand, cases of radiative capture with tritium in the final state were separated under these conditions by means of the range. It was therefore necessary to separate events with deuteron emission from events with proton emission. Figure 1 shows the results of measurements of masses in the 1 pt star group from runs I and III. The foregoing criteria were satisfied by 126 events in run I and 74 events in run III. The obtained histograms were approximated by Gaussian curves with a dispersion equal to 197 MeV/c^2 for the proton mass and 370 MeV/c^2 for the deuteron mass. We see from the figure that the secondary particles in the 1 pt star group are in the main protons, since the probability that the proton can have a mass larger than, say, 1500 MeV/c^2 amounts to less than 3%. Thus, events

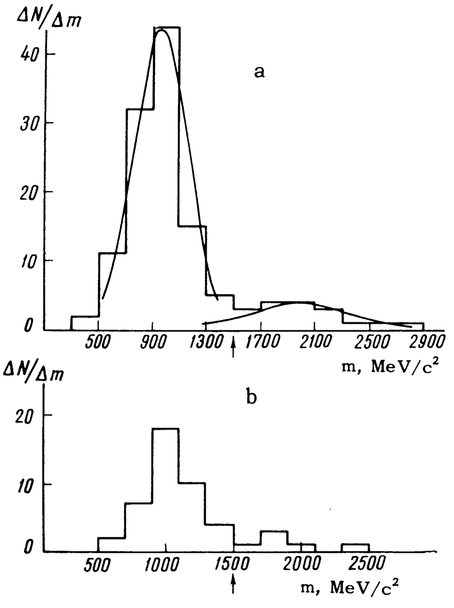

FIG. 1. Mass spectra obtained for measurements of the momentum and of the range in the 1 pt star group: a—run I, b—run III.

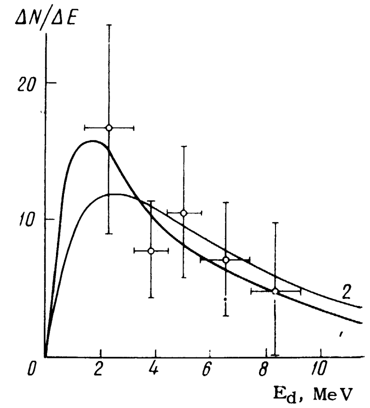

FIG. 2. Energy spectrum of deuterons in reaction (3). Curve 1 represents the spectrum calculated by Struminskiĭ with allowance for the interaction in the final state, curve 2—without allowance for the interaction.

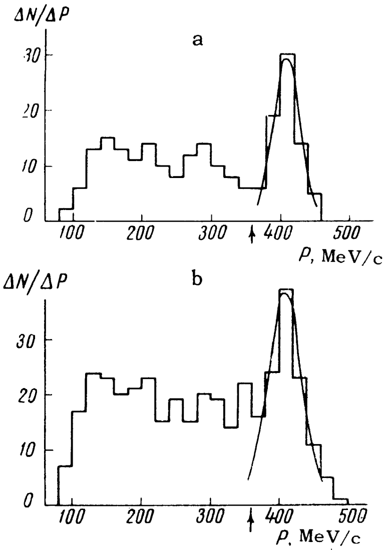

FIG. 3. Momentum spectra obtained in run I: a—with selection criterion of 13 cm track length (the histogram of the events is approximated by a Gaussian curve with dispersion 20 MeV/c); b—with selection criterion of 10 cm track length in the 1 pn star group (histogram approximated by a Gaussian curve with dispersion 23 MeV/c).

with mass larger than 1500 MeV/c can be attributed to process (3).

On the basis of these data we obtained the energy spectrum of the deuterons. In obtaining the spectrum we introduced the geometrical efficiency of registration of a track of given length, calculated by the Monte Carlo method. The number of events with deuterons from run III was related to the number of stopped mesons in run I. The normalization was relative to the number of events of radiative capture in runs I and III. Figure 2 shows the energy spectrum of the deuterons from process (3).

In determining the relative probability of process (3), the energy spectrum was extrapolated to the region of high deuteron energies. The total number of stopped mesons in run I was 4531. As a result, the relative probability of process (3) turned out to be $W(dn\gamma) = (3.6 \pm 1.2)\%$.

THE REACTION $\pi^- + He^3 \rightarrow d + n$

To separate this reaction, we measured in run I the momentum of the secondary particle in the 1 pn star group, inasmuch as process (2) is a two-particle reaction with strictly defined deuteron momentum (414 MeV/c). In measuring the momentum of the secondary particle, we assumed the following selection criteria:

1) The length of the secondary track should be not smaller than 13 cm.

2) The angle of inclination of the track to the plane perpendicular to the magnetic field did not exceed 30°.

The measurements were made by comparing the track with a template of known curvature. In determining the momentum, we took into account the nonuniformity of the magnetic field and the shrinkage of the film. In addition, as a result of the measurement of the track curvature, we introduced a correction for the oblique-angle projection[8]. Figure 3a shows the results of the measurement. At an average momentum 411 MeV/c we observe a monochromatic group corresponding to the momentum of the deuteron from process (2). The histogram of the events, shown in Fig. 3a for the momentum region larger than 360 MeV/c, was approximated by a Gaussian curve with dispersion 20 MeV/c. The background was determined by extrapolating the number of events from the interval 320—360 MeV/c to the point $\overline{P}_d + 2\sigma$. The number of deuteron events depends little on the different assumptions concerning the behavior of the background in the region of momenta larger than 360 MeV/c, and the associated uncertainty is within the limits of the statistical error. After subtracting the background, the observed number of events in reaction (2) was corrected for the registration efficiency. Table I lists the data on the separation of process (2) from run I.

The indicated errors do not include the uncertainties connected with the assumptions concerning the behavior of the background.

The relative probability of process (2) was found to be $W(dn) = (15.9 \pm 2.3)\%$.

Table I

Momentum interval, MeV/c	Observed number of events	Back-ground	Efficiency	Total number of events
360—460	74	6	0,090±0,006	755±105
360—480*	118	11	0,149±0,009	720±90

*This result was obtained with a selection criterion of 10 cm.secondary track length. It was not used in the determination of the relative probability, for in this case the uncertainty in the behavior of the background was already appreciable, owing to the lower accuracy in the momentum measurement.

PROTON MOMENTUM SPECTRUM IN THE PROCESS $\pi^- + He^3 \to p + n + n$

When measuring the momentum spectrum of the protons in reaction (1), we used the 1 pt events from runs I and II, as well as the 1 n events from run I. The proton spectrum in the momentum interval 0—120 MeV/c was obtained by measuring the ranges of the secondary particles. We excluded from the range spectrum of the secondary particles two monoenergetic particle groups corresponding to charge-exchange and radiative-capture processes. No subtraction of the deuterons from reaction (3) was carried out, owing to the small probability of this reaction. In each range interval, we introduced a correction for the geometric registration efficiency. Figure 4 shows the spectrum of protons obtained from measurements of the ranges of the secondary particles in runs I and II. The accuracy in the measurement of the ranges was approximately 1%.

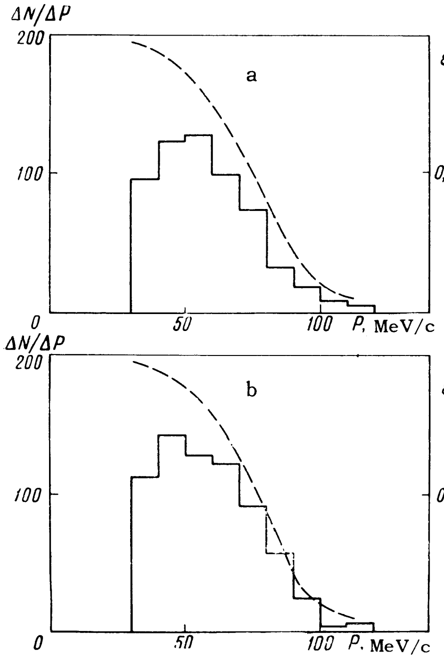

FIG. 4. Proton momentum spectra obtained: a—from run I by measuring the ranges, b—from run II. In both cases the dashed curve gives the efficiency of registration.

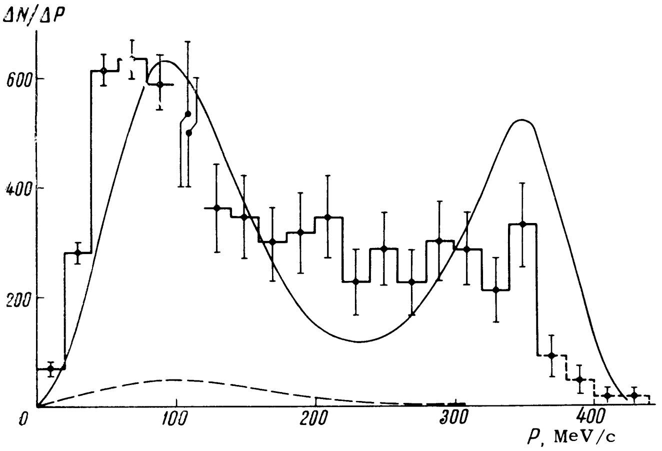

FIG. 5. Pulse spectrum of protons in the process π^- $\pi^- + He^3 \to p + n + n$. The solid curve represents the proton spectrum with allowance for the experimental dispersion of the measurements, as calculated by Divakaran. The dashed curve gives the deuteron spectrum in the process $\pi^- + He^3 \to d + n + \gamma$.

Since protons with 120 MeV/cm momentum were not stopped in the volume of the chamber, the information on the high-momentum part of the spectrum was obtained for measurements of the curvatures of the secondary-particle tracks in the 1 pn star group, using track selection criteria $L \geq 10$ cm and $\alpha \leq 30°$. The measurement results are shown in Fig. 3b. The measured proton spectrum in run I was corrected for the selection efficiency in accordance with the accepted criteria. Inasmuch as the measurement of the particle momentum was made only in run I, this part of the spectrum was normalized to the total number of stopped mesons in runs I and III.

Figure 5 shows the final momentum spectrum of the protons in process (1). The point on the spectrum for the 100—120 MeV/c interval was obtained by two methods: by measuring the ranges of the secondary particles in stars from the 1 pt group, and by measuring the particle momenta from the 1 pn star group. Therefore we show in this interval two points with errors reflecting the statistical uncertainty and the error in determining the efficiency. In the momentum interval 360—480 MeV/c, the proton spectrum is shown dashed, since it was obtained by linear extrapolation of the number of events from the neighboring momentum interval 320—360 MeV/c.

In determining the relative probability of process (1), we excluded events due to reaction (3). As a result, the relative probability of process (1) turned out to be W(pnn) = (7.8 ± 5.4)%.

DISCUSSION OF RESULTS

Divakaran[4] has shown that the ratio of the probabilities of processes (1) and (2) to the probabilities of radiative capture of a pion with tritium in the final state is sensitive to the correctness of the two-nucleon capture model. He calculated the probabilities of processes (1) and (2) by assuming the two-nucleon absorption mechanism and using information on the matrix element of the inverse process, but calculated the probability of the radiative capture with tritium in the final state in terms of the amplitude of pion photoproduction on a single nucleon. We summarize below the experimental data on the relative probabilities of reactions (1), (2), and (3) and the ratios of the probabilities of processes (1) and (2) to the probability of radiative capture, which were measured by us earlier[1]. For comparison we present the values obtained by Divakaran[4].

As seen from Table II, the experimental data on the probability ratios agree with the theoretical ones, but the reliability of the agreement with the theory is low, owing to the large errors in the theoretical quantities, due principally to errors in the amplitudes g_0 and g_1, obtained from the experimental data on the meson-production cross section in NN collisions. It is therefore desirable to have the measured cross sections for meson production near threshold in NN collisions with better accuracy.

Within the framework of the two-nucleon absorption model, it is possible to obtain in independent fashion the ratio of the amplitudes g_1/g_0 on the basis of the experimental value of the probability ratio $W(dn)/W(H^3\gamma)$. As follows from Divakaran's calculations, the probabilities of processes (1) and (2) depend both on the amplitudes g_0 and g_1 and on the relative phase of these amplitudes. The amplitude g_0 describes the transition of the (np) system from the state ($^3S_1$, T = 0) to the state ($^3P_1$, T = 1), while the amplitude g_1 describes the transition ($^1S_0$, T = 1) → ($^3P_1$, T = 1) of the (pp) system. An analysis carried out by Eckstein[5] has shown that the relative phase of the amplitudes g_0 and g_1 can be 0 or 180°. The probability ratio $W(dn)/W(H^3\gamma)$ is sensitive to the relative sign of the amplitudes g_0 and g_1. For $\arg(g_0/g_1) = 0$ it is equal to the quantity given in Table II, whereas for $\arg(g_0/g_1) = 180°$ this ratio is smaller than the measured one by a factor of 4. Thus, the relative phase of the amplitudes g_0 and g_1 is equal to zero. A similar conclusion was obtained also from an analysis of the experiments on the capture of pions by He^4[9]. Using the experimental value of the ratio $W(dn)/W(H^3\gamma)$, we get $g_1/g_0 = 1.3 \pm 0.2$.

Table II

Reaction probability	Experiment (this work)	Theory[4]
$W(pnn)$	$(57,8 \pm 5,4)\%$	—
$W(dn)$	$(15,9 \pm 2,3)\%$	—
$W(dn\gamma)$	$(3,6 \pm 1,2)\%$	—
$\frac{W(pnn)}{W(dn)}$	3.6 ± 0.6	4.6 ± 4.1
$\frac{W(dn)}{W(H^3\gamma)}$	2.3 ± 0.4	1.44 ± 0.68
$\frac{W(pnn) + W(dn)}{W(H^3\gamma)}$	10.7 ± 1.2	8.1 ± 3.8

Further comparison with theory can be based on the obtained proton spectrum in process (1). Divakaran's calculation predicts two broad peaks in the proton spectrum, corresponding to the pion capture by the (np) and (pp) pair. In Fig. 5 the solid curve shows the proton spectrum obtained by Divakaran. The theoretical spectrum was modified by introducing the experimental dispersion of the measurements of the momentum. In comparing the obtained spectrum with the proton spectrum calculated by the two-nucleon capture model, it is striking that the peak corresponding to the capture by the (np) pair is shifted towards smaller proton momenta by an amount ≈ 20 MeV/c, which apparently is due to the coupling of the nucleons in the nucleus. As regards the predicted peak corresponding to capture by the (pp) pair, the experimental spectrum offers evidence that there is no clearly pronounced peak in the 350 MeV/c region

The deuteron spectrum of process (3), obtained in the present work, can be compared with the deuteron spectrum calculated by Struminskiĭ with the aid of a phenomenological potential[10], using experimental data on pion capture in hydrogen. Allowance was made in the calculation for the interaction in the final state in the (nd) system. The solid curves of Fig. 2 shows the theoretical spectrum of deuterons with and without allowance for the interaction in the final state. As seen from this figure, the obtained deuteron spectrum agrees with the calculated one, but owing to the large errors it is not sensitive to the predicted difference in the spectra.

The authors are grateful to B. V. Struminskiĭ and S. S. Gershteĭn for a discussion of the results, and also to A. G. Zhukov, N. V. Lebedev, V. I. Orekhov, V. F. Poenko, A. G. Potekhin, A. I. Tokarskaya, and E. A. Shvaneva for help with the measurements and with the experiments.

---

[1] O. A. Zaĭmidoroga, A. M. Kulyukin, R. M. Sulyaev, I. V. Falomkin, A. I. Filippov, V. M. Tsuppko-Sitnikov, and Yu. A. Shcherbakov, JETP 48, 1267 (1965), Soviet Phys. JETP 21, 848 (1965).

[2] A. M. L. Messiah, Phys. Rev. 87, 639 (1952).

[3] B. V. Struminskiĭ, JINR Preprint E-1012, 1963; Proc. 1962. Intern. Conf. on High-energy Physics at CERN, p. 17.

[4] P. P. Divakaran, Phys. Rev. 139, B387 (1965).

[5] S. G Eckstein, Phys. Rev. 129, 413 (1963).

[6] G. M. Aleksandrov, O. A. Zaĭmidoroga, M. M. Kulyukin, V. P. Peshkov, R. M. Sulyaev, A. I. Filippov, V. M. Tsupko-Sitnikov, Yu. A. Shcherbakov, PTÉ No. 1, 69 (1964).

[7] A. T. Vasilenko, M. S. Kozodaev, R. M. Sulyaev, A. I. Filippov, and Yu. A. Shcherbakov, ibid. No. 6, 34 (1957).

[8] D. B. Pontecorvo, ibid. No. 4, 66 (1964).

[9] R. Bizzaryy, E. De Capua, U. Dore, G. Gialanella, P. Guidoni, and I. Laakso, Nuovo Cimento 33, 1497 (1964).

[10] I. Ya. Pomeranchuk, JETP 22, 129 (1952).

Translated by J. G. Adashko
200