Photoproduction of π^+ in ^{4}He and the Possible Existence of an Unstable ^{4}H State

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New experimental data on the reaction $\gamma+^4\text{He}\rightarrow\pi^++n+t$ are presented, which extend the preliminary results already published by the authors. They confirm the characteristic features of the previous ones, for which the existence of a ^{4}H state unstable against dissociation could be a likely explanation.

INTRODUCTION

WE have reported in a previous paper[1] some preliminary results of an experimental analysis of the reaction:

$$\gamma+^4\text{He}\rightarrow\pi^++n+^3\text{H}. \qquad \text{(I)}$$

The total number of the selected and analyzed events was 96. They were found in a set of 15 000 pictures taken in a diffusion cloud chamber, which was filled with ^{4}He at 8 atm, inserted in a 10 000-G magnetic field and exposed to the 1-GeV bremsstrahlung beam of the Frascati Electron Synchrotron. The analysis of the events was performed only on the basis of angle measurements. In order to explain a marked tendency of π^+ and ^{3}H to be coplanar with the photon direction, we suggested therein the existence of an unstable ^{4}H state, i.e., we assumed that the reaction (I) proceeds as follows:

$$\gamma+^4\text{He}\rightarrow\pi^++[^4\text{H}]\searrow n+^3\text{H}. \qquad \text{(II)}$$

The photon energy, which could not be kinematically determined, was supposed to be 250 MeV for each event. This assumption may have appeared rather arbitrary. However, by doing so, we were able to determine the $\cos\vartheta_{^3\text{H},[^4\text{H}]}$ plot (lab system), which showed a marked tendency of ^{3}H and the $^3\text{H}-n$ center-of-mass to be collinear. Moreover, we were able to determine in a very indirect way the Q value for the decay

$$^4\text{H}\rightarrow{}^3\text{H}+n \qquad \text{(III)}$$

which was found to be (3.5–7) MeV.

Our interpretation of the results obtained, based on the existence of a ^{4}H state unstable against dissociation, has received some criticism[2,3] which we will discuss in detail at the end of this paper.

There is indeed at present a certain interest in the problem of the existence of such a state, because of its connections with many recent experiments and theoretical speculations concerning the few nucleon problems, while, on the contrary, the existence of a ^{4}H state stable against dissociation has been definitely contradicted by the results of many authors.[4]

In order to extend our previous results with further data and, above all, to examine the likelihood of the assumptions made in the first paper, we have proceeded to a second exposure of the cloud chamber to the photon beam and we have taken 25 000 new pictures under the same experimental conditions as in the first work, with the purpose of finding a set of events belonging to the reaction (I), which is completely determined from the kinematical point of view.

EXPERIMENTAL PROCEDURE

The experimental apparatus was described in greater detail in a previous paper.[5] Therefore we will give here only an account of the analysis criteria adopted. To select from the total set of 40 000 pictures the two-prong events belonging to the reaction (I) and susceptible of a complete kinematical analysis, we have imposed the following conditions: (a) The event has to be found in a fiducial zone of the diffusion chamber; (b) one prong must be "at minimum" of ionization ("grey") and the other "black"; (c) the "grey" prong must satisfy with close approximation the momentum-ionization curve for pions (Fig. 1); (d) the momentum of the "black" one has to be measurable. Only 51 events satisfying

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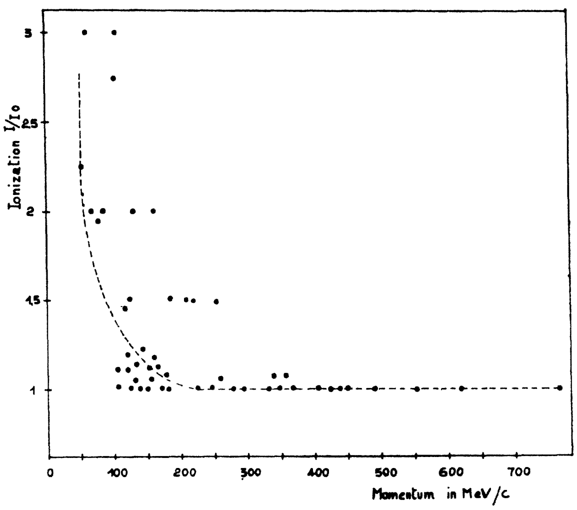


FIG. 1. Ionization–momentum plot for the selected π^+. The ionization was estimated by comparing the prong of the π^+ with that of an electron or with the overlapping of two or three electron prongs in the same picture in which the π^+ was found. The experimental error in the momentum measurements is about 15%. The dashed curve is a best fit of the experimental distribution for the π^-.

these conditions were found. The smallness of this number is due mainly to the (a) and (d) selection tests.

We are not sure that the "black" particle is a triton, because its ionization is very difficult to estimate and we could measure both momentum and range only in few cases. However, if we assume that every "black" particle is a triton, we never find a contradiction between its length (or range) and its momentum. On the other hand, on the basis of some data which we have collected on the mirror reaction ${}^4\mathrm{He}(\gamma,\pi^-)p,{}^3\mathrm{He}$, we can state that the contamination of particles other than tritons is less than 20% and above all that, in any case, the reactions involved are three-or-more-body

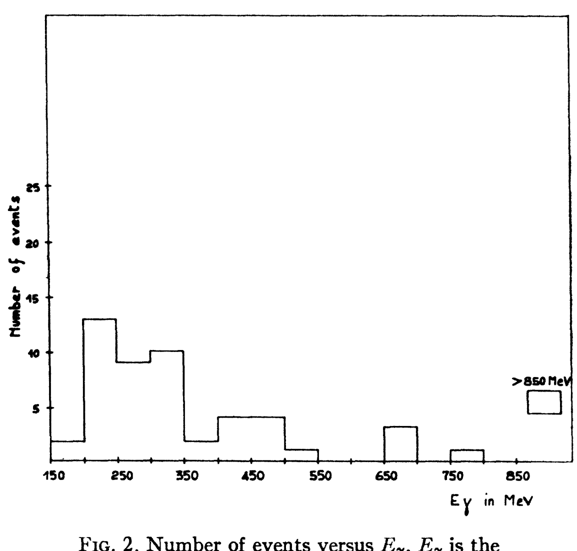


FIG. 2. Number of events versus E_γ. E_γ is the photon energy in the lab system.

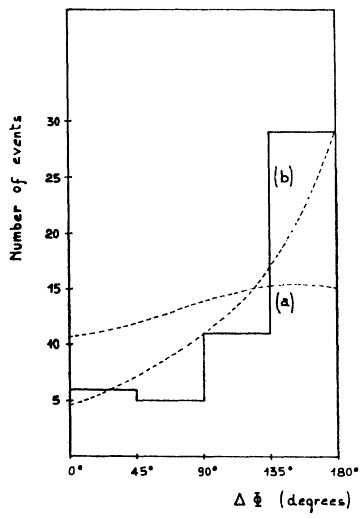


FIG. 3. Number of events versus $\Delta\phi$. $\Delta\phi$ is the angle between the production planes of π^+ and ${}^3\mathrm{H}$. Curve (a) represents the Von Hippel and Divakaran distribution calculated in the impulse-approximation model (Ref. 3); curve (b) represents the Lohrmann *et al.* distribution calculated in the statistical model (Ref. 2).

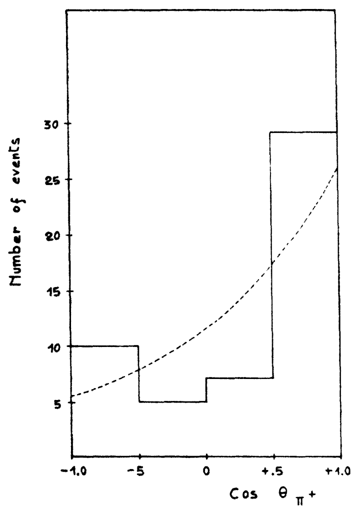


FIG. 4. Number of events versus $\cos\vartheta_{\pi^+}$. ϑ_{π^+} is the angle between the π^+ direction and the photon direction in the lab system. The dashed curve represents the Von Hippel theoretical distribution (Ref. 3).

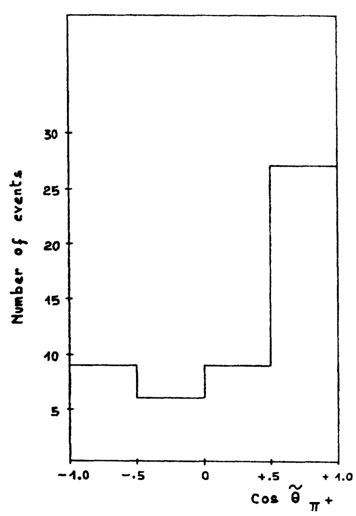


FIG. 5. Number of events versus $\cos\tilde{\theta}_{\pi^+}$. $\tilde{\theta}_{\pi^+}$ is the angle between π^+ and γ in the c.m. system.

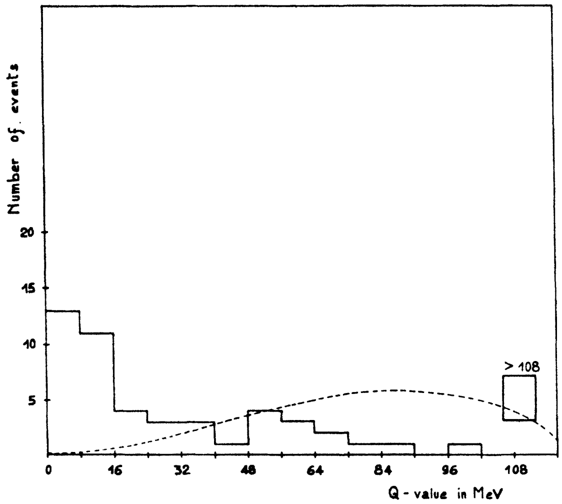


FIG. 6. Number of events versus Q. Q is the total kinetic of n and ^{3}H in their center-of-mass system, i.e., the Q value of the decay $^4\text{H} \rightarrow n + {}^3\text{H}$ (real or virtual decay). The dashed curve represents the Von Hippel theoretical distribution (Ref. 3).

ones. Moreover, the fact that the E_γ plot (Fig. 2) agrees with what one would expect on the basis of the π^+ photoproduction cross section on free nucleons supports the assumption made.

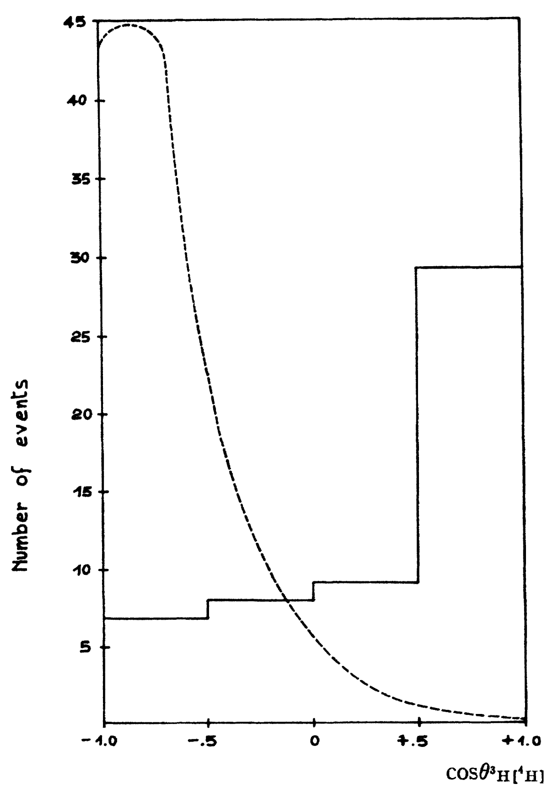
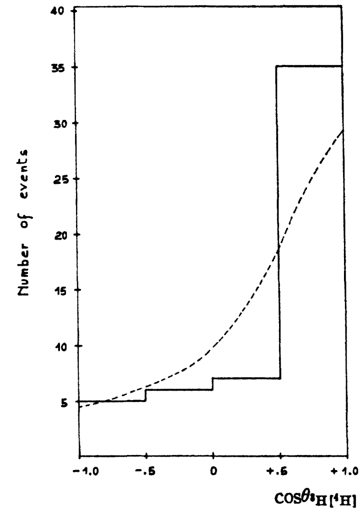


FIG. 7. Number of events versus $\cos\vartheta^3{}_{\text{H},[^4\text{H}]}$. $\vartheta^3{}_{\text{H},[^4\text{H}]}$ is the angle (in the lab system) between the measured direction of ^{3}H and the calculated direction of the center of mass of the $n-{}^3$H system (with its calculated effective mass $M = m_n + m_T + Q$). The dashed curve represents the Von Hippel calculated distribution (Ref. 3).

FIG. 8. Number of events versus $\cos\vartheta^3{}_{\text{H}[^4\text{H}]}$. The same as in Fig. 7, but in the center-of-mass system. The dashed curve represents the Von Hippel calculated distribution (Ref. 3).

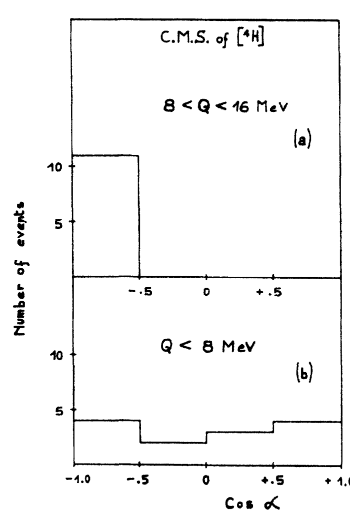


RESULTS

The results obtained are summarized by Figs. 1 to 9 and by the figure captions.

In spite of the poor statistics, due mainly to the rather strong selection tests for the reaction (I), we can remark that the present results agree very well with the old ones and that they confirm also every assumption made at that time (in particular the assumption made on the value of E_γ). We wish above all to stress that in the present work the Q-value distribution is directly determined by the kinematics, while in the previous paper[1] the Q value for the decay (III) was estimated only in a very indirect way. The distributions found are plotted without consideration for the experimental errors in the angle and momentum determination. [The experimental error is about 15% for the momentum measurements and 2°–3° for the angle measurements.] However, we also have made a calculation in which we have taken into account the experimental errors by representing each event with a proper Gaussian curve, but the modifications of the plots have been found to be completely negligible.

FIG. 9. Number of events versus $\cos\alpha$. α is the emission angle of ^{3}H in the $n-{}^3$H center-of-mass system. Plot (b): events with $Q<8$ MeV; Plot (a): events with $8<Q<16$ MeV.



DISCUSSION

Although the results of both the first and the present work cannot be conclusive for the existence of a ^{4}H state unstable against dissociation, we do not think that the criticism which has been advanced against our interpretation of them can invalidate its likelihood.

The first criticism was made by Lohrmann *et al.*[2] In their paper the $\Delta\phi$ distribution between two particles in a general three-body reaction is calculated. The calculation is performed on the basis of the statistical model, i.e., only transverse momentum conservation is assumed and any interaction between n and ^{3}H is neglected. The result is found to be in good agreement with our old experimental $\Delta\phi$ distribution and it also agrees substantially with the present one (Fig. 3). It is clear, however, that the assumed model is inadequate, because the reaction (I) involves nucleons and pions and the simplest model for reactions of this type is the impulse approximation[6] and not the statistical model. We think therefore that either the agreement between Lohrmann's calculation and our results is accidental or it involves some untrivial consequences (e.g., the validity of the statistical model for this particular reaction). Hence, in any case, the tendency of π^+ and ^{3}H to be coplanar with the photon direction is not a trivial kinematical effect.

This point was understood by Von Hippel and Divakaran,[3] who compared all the distributions plotted by us in the first work with the results of an impulse approximation calculation, in which they assumed no final-state interaction between n and ^{3}H. Every calculation was performed by putting $E_\gamma = 300$ MeV, because the authors found that the results are not affected by the E_γ value in the range 200–400 MeV. Unfortunately there was an ambiguity, because these authors calculated the $\cos\vartheta_{^3\text{H},[^4\text{H}]}$ distribution in the center-of-mass system, while we had plotted ours in the laboratory system (L. S.); therefore the two distributions could not be directly compared.

From the comparison between Von Hippel and Divakaran calculations[3] and the present experimental results we think that the following considerations can be made:

(1) The calculated $\Delta\phi$ distribution shows a slight tendency to be peaked towards 180°, while this tendency seems to be stronger in our plot (Fig. 3).

(2) The calculated $\cos\vartheta_{\pi^+}$ (L. S.) distribution agrees substantially with ours (Fig. 4).

(3) The calculated Q-value distribution is in strong disagreement with ours which is peaked at low values (Fig. 6).

(4) The calculated $\cos\tilde{\vartheta}_{^3\text{H}[^4\text{H}]}$ distribution in the center-of-mass system agrees with ours (Fig. 8), but there is a strong disagreement between the two distributions in the lab system (Fig. 7). In fact the calculated one is peaked backwards in the lab system[7] while ours is peaked forward in both systems. This fact occurs because the average effective mass of the $n-{}^3$H system is less than the calculated one (Fig. 6) and therefore its translational energy must be larger than the predicted one. For this reason in the Von Hippel calculations the ^{4}H-direction is strongly affected by the reference frame, while in our case the direction is about the same in both frames.

In conclusion we may state that our assumption of the existence of a ^{4}H state with a Q value for the decay (III) less than 8 MeV has not lost its likelihood and that it may be a good explanation for the main features of our results and for some disagreement between these and the theoretical calculations.

Figure 9 shows that, apart from the very poor statistics, the angular distribution of ^{3}H in the $n-{}^3$H center-of-mass system for the events with $Q<8$ MeV is symmetric around 90° and therefore it is not in contradiction with the existence in the $n-{}^3$H system of a definite angular momentum. For $Q>8$ MeV the distribution is no longer symmetric probably because of the presence of interferential terms between various waves.

In a recent experimental investigation of the reactions ^{7}Li$(\pi^-,{}^3$H$)^4$H and ^{6}Li$(\pi^-,{}^2$H$)^4$H, Cohen *et al.*[8] have found strong evidence for the existence of a ^{4}H state with an energy for the decay $n+t$ of about 5 MeV, which, it would seem, constitutes a quite satisfactory confirmation of our hypothesis. Unfortunately, from the Q distribution given in the present work it is impossible to determine the decay energy of the ^{4}H state (if it does exist).

The assignment $T=1$ for the isotopic spin of ^{4}H seems to us to be at present the most probable one. Indeed the assignment $T=2$, which was suggested[9] to take some evidence for the existence of ^{5}H [10] into account, has lost its validity, because many recent experiments seem to completely invalidate the above evidence.[11]

ACKNOWLEDGMENTS

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Many thanks are due also to Dr. F. Von Hippel for the very useful correspondence concerning the results of our experiment.

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