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BRIEF REPORTS

Brief Reports are short papers which report on completed research or are addenda to papers previously published in the **Physical Review.** *A Brief Report may be no longer than 3½ printed pages and must be accompanied by an abstract.*

Search for the tetraneutron using the reaction $^4He(\pi^-,\pi^+)^4n$

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A search for the production of bound tetraneutrons has been carried out with a time projection chamber using the reaction $^4He(\pi^-,\pi^+)^4n$ at $T_{\pi^-}=80$ MeV and at $50° < \theta_{lab}^{\pi^+} < 130°$. No evidence for tetraneutron formation was found, and a 90% confidence level upper limit for the production cross section of $d\sigma/d\Omega \leq 13$ nb sr^{-1} was obtained.

The possibility of bound clusters of neutrons has been a long standing object of theoretical speculation and experimental investigation. The existence of a bound tetraneutron (^4n) has been examined by a number of authors, and while considered unlikely, the difficulties in dealing with many-body systems lead to no truly reliable predictions.[1–6] As a result, numerous experiments using a variety of approaches have searched for the tetraneutron, but none has provided any convincing evidence for its existence. A summary of some of the experimental searches for the tetraneutron has been compiled by Fiarman and Meyerhof.[7] All searches, however, have necessarily involved rather exotic reactions and consequently rather low cross sections for ^4n production even in the event of its existence.[8]

The pion double charge exchange (DCX) reaction $^4He(\pi^-,\pi^+)^4n$ is an attractive candidate for a tetraneutron search, and has been the subject of several earlier experiments.[9–14] The two-body final state allows relatively simple recognition of tetraneutron production signaled by the emission of monoenergetic π^+'s, whose energy is determined by the tetraneutron's binding energy. Recently, Ungar *et al.*[13] have measured the π^+ energy spectrum at $\theta_{lab}^{\pi^+}=0°$ and incident pion energy $T_{\pi^-}=165$ MeV, and obtained an upper limit on the production cross section for bound tetraneutrons of $d\sigma/d\Omega \leq 22$ nb sr^{-1} (1σ).

Here we report the results of an experiment using the same reaction, but with incident π^-'s of 80 MeV ($P_{\pi^-}=170$ MeV/c) and with the π^+ energy spectrum measured over an angular range from 50° to 130°. The production of just-bound tetraneutrons would appear as a peak in this energy spectrum at 50 MeV (128 MeV/c). The maximum possible π^+ energy is 53 MeV (133 MeV/c), a consequence of the 3 MeV upper limit on the tetraneutron binding energy due to the absence of the decay $^8He \rightarrow ^4He + ^4n$). The lower incident π^- energy is a major advantage, since it dramatically reduces the phase space available for continuum double charge exchange $^4He(\pi^-,\pi^+)4n$ and hence this source of background. However, a disadvantage of the angular range 50° to 130° is that it selects a higher momentum transfer to the final-state neutrons than that of the experiment of Ungar *et al.*[13]

The experiment was performed using the TRIUMF time projection chamber (TPC) (see Fig. 1).[15] The capa-

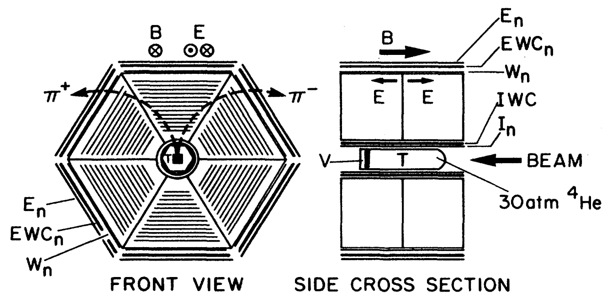

FIG. 1. The TPC front and side cross section. All the triggering counters (I_n, IWC, W_n, EWC_n, E_n) are shown as well as the direction of the magnetic (B) and electric (E) field, the beam direction (BEAM) and the target T. The twelve straight lines inside every sector of the TPC are the anode wires; the cathode pads under the anode wires are not shown. The two dashed semicircles coming from the center are examples of $x-y$ projections of tracks of negative and positive particles.

bility of this instrument for measuring pion double charge exchange has previously been demonstrated by the $^{14}C(\pi^+,\pi^-)^{14}O$ experiment of Navon *et al.*[17] The TPC is a large volume drift chamber situated in parallel electric and magnetic fields, and offers a large solid angle ($\sim 50\%$ of 4π) with reasonable pion momentum resolution (3% σ at 128 MeV/c). Ionization electrons from charged particle tracks in the chamber gas drift to the endcaps where an array of proportional wires provide up to 12 (x,y,z) track coordinates using the location and time at which each wire is struck. From the reconstructed track the particle's momentum, direction, and approximate origin can be determined. Particle identification was possible using dE/dx information.

At 80 MeV the low-energy π/μ channel ($M9$) at TRIUMF provided 2×10^6 π^-/sec in a 5% dp/p momentum bite, with a 5×5 cm^2 full width at half maximum (FWHM) spot size. The electron and muon contaminations were less than 10% and 5% respectively, and were easily distinguished by their time of flight along the beamline. The target vessel was an aluminum flask, 17 cm in diameter and 50 cm in length, with a 0.7 g cm^{-2} thick entrance window. It contained helium gas at a pressure of 30 bars, giving a total ^{4}He target thickness of 0.27 g cm^{-2}. The pion flux passing through the target was measured using an internal scintillator situated at the rear of the flask. This scintillator also provided normalization and a means of rejecting background associated with the back wall of the flask. The beam defining counters normally placed in front of the TPC were removed for this experiment, in order to reduce the trigger rate from scattered beam particles.

Particles of sufficient momentum that exited the target flask in the angular range 50° to 130° passed through a layer of inner trigger scintillators (I_n) and a cylindrical wire chamber (IWC) before traversing the TPC and hitting two further layers of outer trigger scintillators (E_n and W_n), and a wire chamber (EWC_n) as shown in Fig. 1. Each of the three layers of scintillators has six-fold segmentation. The trigger required a coincidence between an inner and outer scintillator, with the outer counter being one segment counterclockwise from the hit inner counter. This selected tracks produced by positively charged particles, allowing significant reduction of the otherwise intolerable trigger rate due to π^- elastic scattering.

Despite the positive curvature requirement, the majority of valid triggers were still due to negative pions that had scattered in the inner scintillators. In the subsequent analysis they were easily eliminated using their direction of curvature as determined from the TPC track information.

The remaining events consist of positrons, protons, and DCX π^+'s. The positrons resulted from the conversion of photons from π^0 decays, following (π^-,π^0) single charge exchange reactions. The protons were most likely the consequence of π^- capture and (π^-,p) knockout reactions. Their momenta were predominantly above 200 MeV/c. Software cuts, the most effective being ionization density in the TPC and energy deposited in the trigger scintillators, were applied to remove both the protons and positrons. At the momenta of interest proton energy loss is one order of magnitude greater than pion energy loss, and consequently the proton contamination was easily eliminated. However, the rejection of positrons was less certain. The problem is illustrated by Fig. 2 which shows the TPC ionization density versus momen-

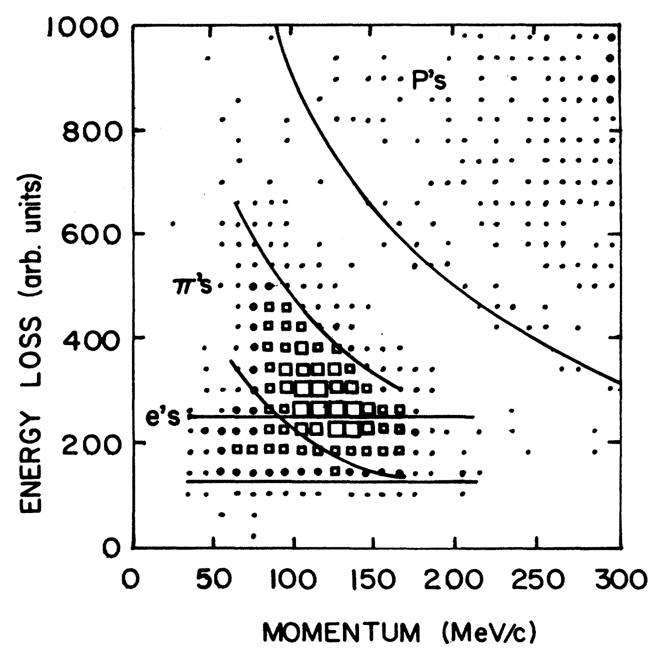

FIG. 2. Momentum vs TPC ionization density for recorded events, before software cuts. The main components are (i) protons from π^- capture and (π^-,p) knockout reactions, (ii) π^-'s scattered from the target walls and trigger scintillators, and (iii) positrons due to photon conversion, the photons originating from π^0 decays following (π^-,π^0) reactions. The protons are mainly above 200 MeV/c and highly ionizing, whilst the pion energy-loss band is falling rapidly towards minimum ionizing in the region of 100 MeV/c. The positrons are peaked around 70 MeV/c and are minimum ionizing.

tum for all recorded events. Above 90 MeV/c the π and e energy-loss bands begin to overlap, and by 120 MeV/c this overlap is considerable.

Many of the π^+ events originated not from the helium, but from the target flask. The front and back wall contributions were removed by a cut on the reconstructed origin of the track along the beam axis. However, poor determination of the track's radial origin meant that the same procedure could not be applied to eliminate the much smaller side wall background. Instead empty target runs were used to measure this contribution. Several target-empty and target-full runs were taken to verify the consistency of this procedure.

The acceptance and the momentum resolution for 50 MeV (128 MeV/c) π^+'s were determined using π^+ ^{4}He elastic scattering. Figure 3 shows the measured momentum spectrum for π^+ ^{4}He elastic scattering after software cuts and background subtraction. The beam intensity was 3.3×10^6 π^+/sec, with the same momentum bite as the π^- beam. The measured resolution is 11 MeV/c (σ), due almost entirely to the beam momentum resolution of 9 MeV/c. The acceptance was determined to be $\epsilon\Omega=0.31$ steradians by normalization to the differential cross sections of Fournier *et al.*[16]

The TPC efficiency was found to be rate dependent; as the flux of charged particles through the TPC increased, a corresponding decrease in efficiency was observed. This is believed to be a consequence of the increasing number of positive ions surrounding the TPC anode wires, an effect documented by Sauli.[18] These positive ions reduce the gas multiplication and hence the pulse heights, thereby lowering the chamber acceptance. Consequently the measured TPC acceptance had to be corrected for the difference in rates between the $T_{\pi^+}=50$ MeV and $T_{\pi^-}=80$ MeV measurements. Since the rate of charged particles through the chamber was considerably lower for the π^- beam it amounted to an upward correction of the TPC acceptance to $\epsilon\Omega=0.51\pm0.06$ steradians. Further details of this procedure and the TPC rate dependent acceptance are given in Armstrong *et al.*[19]

Figure 4(a) shows the final DCX π^+ momentum spectrum after all cuts. It represents a total of $N_{\pi^-}=6.01\times10^{10}$ incident negative pions. In the tetraneutron window (128$\pm$11 MeV/c) there are 12 counts. These counts are, however, consistent with various sources of background, rather than evidence for the production of tetraneutrons.

Firstly, there is a background contribution from the side walls of the target flask. In the same energy window in the target-empty spectrum there are 7 counts from a total of $N_{\pi^-}=7.07\times10^{10}$ incident negative pions. Figure 4(b) shows the DCX π^+ spectrum after subtraction (normalized to the same number of incident pions) of the measured empty flask background. After this subtraction just 6.1 counts remain in the tetraneutron window. Secondly, due to our limited momentum resolution there is a contribution from ^{4}He(π^-,π^+) continuum DCX. A rough estimate of this contribution to the tetraneutron window was obtained as follows. The region 106$\pm$11 MeV/c of spectrum 4(b) contains 20 counts (the e^+ contamination in this window is $\leq20\%$). With $\sim$20 π^+ counts in this -1σ to $+1\sigma$ window, one would expect $\sim$5 counts between $+1\sigma$ and $+3\sigma$, the tetraneutron window. This estimate of 5 counts from continuum DCX on ^{4}He is consistent with the 6.1 remaining counts in the target full-target empty spectrum. Finally, we cannot ex-

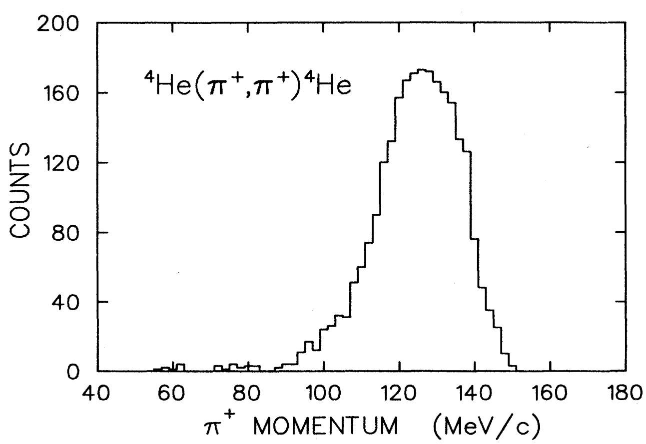

FIG. 3. Measured π^+ momentum spectrum from ^{4}He(π^+,π^+)^{4}He elastic scattering at $P_{\pi^+}=128$ MeV/c ($T_{\pi^+}=50$ MeV). The observed momentum resolution is 11 MeV/c (σ).

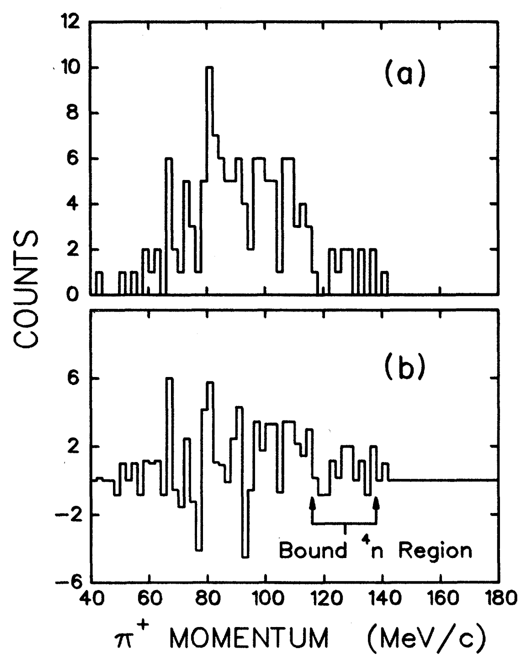

FIG. 4. (a) Measured π^+ momentum spectrum from ^{4}He(π^-,π^+) at $P_{\pi^-}=170$ MeV/c ($T_{\pi^-}=80$ MeV) and $\theta=50°-130°$, after all software cuts. The region corresponding to bound tetraneutron production (indicated by the arrows) contains 12 events. (b) The same spectrum after subtraction of the empty-target background. The region corresponding to tetraneutron production contains 6.1 events.

clude a contribution from misidentified positrons in the tetraneutron region. The considerable overlap of the π and e energy-loss bands in this region makes it difficult to estimate this contribution. However, since the expected background of ~ 6 counts from the flask and ~ 5 counts from ^{4}He continuum DCX is consistent with the observed 12 counts, we conclude that the positron contamination is small.

To calculate the cross-section limit on tetraneutron production we take the observed 12 counts in the tetraneutron window and the measured background of ~ 6 counts due to the flask walls. We do not include the additional 4 background counts estimated for ^{4}He continuum DCX since this estimate is somewhat crude and we wish to make a conservative cross section limit. These counts yield[20] a 90% confidence level limit of $N_{4_n}=12$ counts on a tetraneutron signal. From this the following cross-section limit on tetraneutron production is obtained:

$$\frac{d\sigma}{d\Omega} \le \left[\frac{N_{4_n}}{f}\right] \Big/ \left[N_{\pi^-}\left[\frac{N_A}{A}\rho t\right]_{\rm tgt}\epsilon\Omega\right]$$
$$\le 13\ \mathrm{nb\,sr^{-1}}\ ,$$

where $f=0.68$ is the fraction of events within $\pm 1\sigma$ of the peak centroid, $[(N_A/A)\rho t]_{\rm tgt}$ is the target thickness in nuclei/cm^2, N_{π^-} is the deadtime corrected number of incident π^-'s, and $\epsilon\Omega$ is the detector acceptance.

The cross-section limit of $\le 13\ \mathrm{nb\,sr^{-1}}$ is almost a factor of 2 lower than the limit set by Ungar *et al.*,[13] however it should be pointed out that the momentum transfer in the present experiment is higher. This makes a direct comparison of the two limits somewhat difficult. Certainly though, neither this experiment nor any of the previous searches can be viewed as absolutely excluding the existence of the tetraneutron. Finally, perhaps a more sensitive search using the ^{4}He$(\pi^-,\pi^+)^4n$ reaction should be undertaken, likewise with low-energy incident π^-'s, but measuring the π^+ energy spectrum at forward angles instead.

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