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Short note

Search for a bound trineutron with the ^{3}He(π^-,π^+)nnn reaction

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Abstract. A search for the production of a bound trineutron state has been performed using the reaction ^{3}He(π^-,π^+)nnn at incident pion energies of 65, 75, and 120 MeV. No evidence for the existence of the ^{3}n was found, and an upper limit for the production cross section of approximately 30 nb/sr (2σ confidence level) was obtained.

PACS. 21.45.+v Few-body systems – 25.10.+s Nuclear reactions involving few-nucleon systems – 25.80.Gn Pion charge-exchange reactions

Few-nucleon systems have since long been an ideal testing ground for nuclear models and the underlying nucleon-nucleon interaction. A straightforward way to perform such tests is to compare experimentally determined energy levels with the corresponding theoretical calculations. While the ground states of A=3 and A=4 nuclei are rather insensitive to the various theoretical approaches, the predictions of extreme nuclear configurations such as ^{3}n and ^{4}n show a much enhanced sensitivity to nuclear potentials [1,2]. Thus the investigation of those multi-neutron systems seems appropriate to elucidate fine details of the nuclear interaction. Most theoretical approaches are based on realistic nucleon-nucleon potentials which are extracted from phase shifts analyses of nucleon-nucleon scattering data. Independent of the theoretical framework, such as the Faddeev formalism or variational calculations, most theoretical works do not predict a bound ^{3}n state in the three-neutron system. However, it has been stressed [3] that subtle changes in the nucleon-nucleon potential — which would not affect results from phase shifts analyses — may lead to bound neutronic nuclei. The question of low-lying 3n resonances was studied by Glöckle [4], who ruled out the possibility of low-lying $J^\pi = \frac{1}{2}^+$ resonances in his model. However, a more recent calculation [5] predicts a $J^\pi = \frac{3}{2}^+$ state at E=11-14 MeV with a width of Γ=13 MeV in the 3n system. Although such a resonance would fit very well to early interpretations [6] of data on the pionic double charge exchange (DCX) on ^{3}He, more recent DCX investigations [7] do not see any experimental evidence for it. Apart from these aspects the question whether multi-neutron systems exist is of principal interest by itself.

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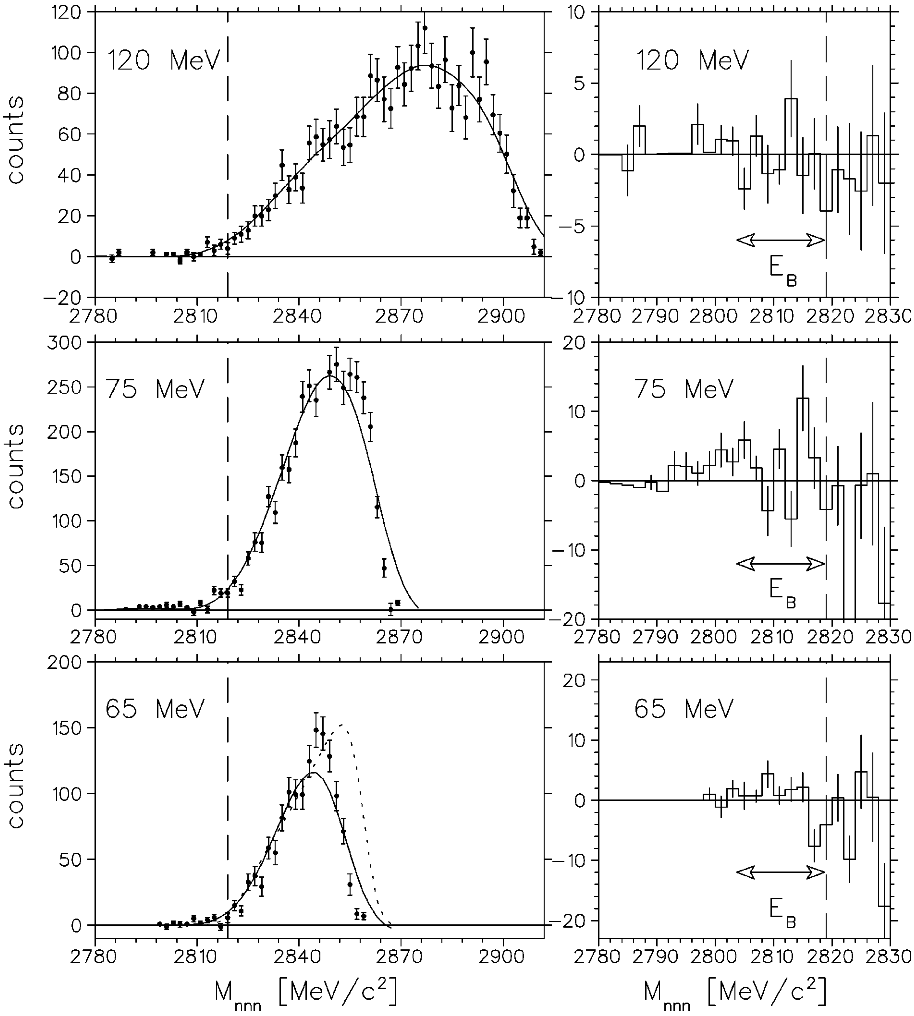

Fig. 1. Invariant mass of the three-neutron system. Left: Experimental data points. The dashed line indicates the kinematical limit of three unbound neutrons. The solid lines are cubic spline fits that are used to approximate the contribution from unbound neutrons in the kinematically forbidden region. The dotted curve represents a 4-body phase space distribution. See text for details. Right: Difference of experimental data and the fitted contribution of unbound neutrons

In the past, searches for trineutrons were conducted in four types of reactions: ^{3}H(π^-, γ)^{3}n, ^{3}He(π^-, π^+)^{3}n, ^{4}He(π^-, p)^{3}n and heavy ion reactions such as ^{7}Li(^{11}B, ^{15}O)^{3}n. As of yet, none of these reactions provided evidence for a bound trineutron. For a detailed discussion of previous measurements see [8]. Upper limits for the production cross section of ^{3}n in heavy-ion reactions [9] were determined to be 10 nb/(sr·MeV). From the study of DCX at T_π = 140 MeV an upper limit of 120 nb/sr was found [10].

To get an idea what the production cross section of a bound trineutron in DCX reactions could be, we consider a similar system. The DCX reaction ^{7}Li(π^+,π^-)^{7}B leads to a particle-unstable nucleus that, in a naive picture, consists of a helium core and a three-proton halo [11]. The cross section for the ground state transition which includes the formation of a quasi-bound three-nucleon system was found to be in the order of 100 nb/sr [11]. Therefore, the limit of 120 nb/sr deduced in [10] might not be stringent enough to exclude the existence of a trineutron. This argument is further supported by the fact that the ^{7}Li(π^+,π^-)^{7}B reaction is an intra-shell transition whereas the ^{3}He(π^-,π^+)^{3}n would involve a cross-shell transition with a correspondingly smaller cross section.

In this work we examine the DCX reaction ^{3}He(π^-,π^+) at three incident pion energies, 65, 75, and 120 MeV. At such low pion energies the typical recoil energy transferred to the three-neutron system is only several MeV, which is the same order of magnitude as the expected binding energy of a hypothetical trineutron. Thus intuitively it appears more likely to produce a trineutron in such a "soft" reaction than at higher energies.

The experimental apparatus used was the CHAOS (Canadian High Acceptance Orbit Spectrometer) detector [12,13] and a liquid ^{3}He target. CHAOS is a magnetic spectrometer that allows momentum reconstruction of the scattered particles with a momentum acceptance from 50 MeV/c up to the kinematic limit. The angular coverage is almost 360° (except for holes in the regions of the incoming and outgoing beam) in-plane and ±7° out-of-plane. The particle identification is performed using an array of plastic scintillators and lead glass Cerenkov counters that surround the detector. CHAOS provides a sophisticated hardware trigger which is capable of detecting the polarity change that identifies a charge exchange reaction. The target was the same as was used previously [14] for DCX measurements on ^{4}He except for minor modifications that were necessary in order to condense ^{3}He.

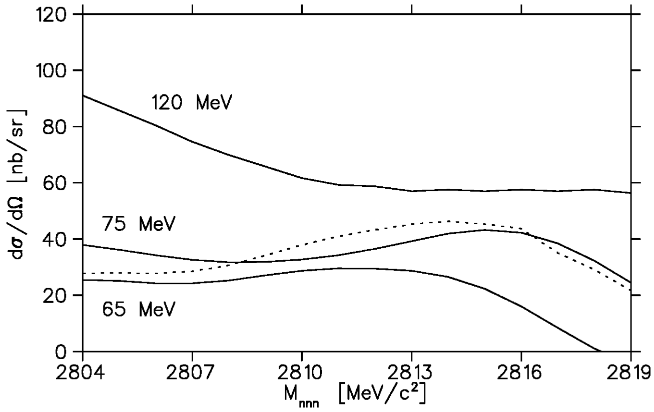

Fig. 2. Upper limits (2σ confidence level) for the ^{3}n production versus its assumed mass at various incident pion energies. The solid curves are results from the spline fits and the dotted curve is the result of the 4-body phase space distribution at 65 MeV. See text for details

From the momentum of the incoming π^- and the reconstructed momentum of the outgoing π^+ the invariant mass M_{nnn} of the three-neutron system has been reconstructed for all events within the CHAOS acceptance. The data reduction and normalization procedure is described in detail in [15]. On the left of Fig. 1 M_{nnn} is shown for 120, 75, and 65 MeV. It is seen that the three-neutron invariant mass distributions leak into the region (see dashed curve in Fig. 1) that is kinematically forbidden for a final state of three unbound neutrons. However, this has not necessarily to be ascribed to a bound trineutron but could be due to the finite resolution of the reconstructed invariant mass. In order to determine this "conventional" contribution in the kinematical region of a bound trineutron, a cubic spline fit was performed to account for the finite resolution. The boundary conditions of the fit were a constant background for $M_{nnn} < 2803.7$ MeV for $M_{nnn} > 2818.7$ MeV a trineutron with a binding energy $0 < E_B < 15$ MeV ($E_B > 0$ for bound states) do not affect the spline fit which then represents the true physical background. On the right hand side of Fig. 1 the difference between the spline fit and the experimental data is shown. No statistical significant structure can be seen. In order to determine an upper limit for the ^{3}n production cross section Gaussian shaped distributions were fitted to the difference spectra for binding energies $E_B < 15$ MeV. The widths of the Gaussian distributions were kept fixed at a value corresponding to the appropriate detector resolution. The resolution was determined by GEANT Monte Carlo simulations to be 5.3, 3.5, and 3.0 MeV at 120, 75, and 65 MeV, respectively. This procedure results in upper limits (2σ confidence level) for the ^{3}n production cross sections as given in Fig. 2.

In order to test the above procedure an alternative method was used. Due to the lack of a reliable model for the DCX reaction at low energies an attempt was made to describe the experimental data under the assumption of a simple 4-body phase space distribution in the final state. After consideration of the detector resolution and acceptance it was found that a reasonable description of the invariant mass spectra above threshold could be obtained. Again upper limits for the ^{3}n production were obtained from the analysis of the difference of the experimental data and the 4-body phase space distribution. The limits that were obtained using this procedure are somewhat larger but in qualitative agreement with the results from the spline fit. Exemplarily, the 4-body phase space distribution and the resulting upper limits are shown for 65 MeV as the dotted curves in Fig. 1 and Fig. 2.

In order to search for the predicted [5] unbound three-neutron resonance with mass 2820-2823 MeV/c^2 the experimental resolution and the predicted width of 13 MeV were taken into account and a Gaussian fit to the difference spectrum of the data and the spline fit was performed. The obtained upper limits (3σ confidence level) for the formation cross section of such a resonance are 640, 72, and 48 nb/sr at 120, 75, and 65 MeV, respectively.

To summarize, the ^{3}He(π^-,π^+) reaction has been examined at 120, 75, and 65 MeV. Invariant mass spectra were obtained for the three-neutron system and no evidence for a bound trineutron state has been found. The deduced 2σ upper limits (≈ 30 nb/sr) for the ^{3}n production are the most stringent limits obtained in DCX on ^{3}He. Also no signal of an unbound three-neutron resonance could be observed.

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