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The $t + n + n$ System and ^{5}H

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The one-proton knockout channel from ^{6}He (240 MeV$/u$) impinging on a carbon target has been investigated. The triton fragments originating from this channel were detected in coincidence with the two neutrons. A broad structure, peaked at 3 MeV above the $t + 2n$ threshold, is observed in the $t + n + n$-relative energy spectrum. It is shown that this structure is mainly due to a $I^{\pi} = 1/2^{+}$ resonance as expected for the ^{5}H ground state, and from the observed angular and energy correlations, being used for the first time in ^{5}H studies, that the neutrons to a large extent occupy the p shell.

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There is at present a lively debate concerning the existence of ^{5}H as a narrow low-energy resonance state. The results presented in this Letter give—for the first time—access to internal correlations in the ^{5}H system. This new and, as we feel, decisive information may be used to settle this important problem.

The structure of an unbound heavy hydrogen system ($A \geq 4$) is expected to be similar to that of neutron-rich helium isotopes, namely, an inert core surrounded by valence neutrons [1–3]. In this Letter we discuss the $t + n + n$ system relevant for ^{5}H. The experimental studies of ^{5}H started four decades ago with evidence that it is β-unstable with a half-life of about 100 ms [4]. Since then, the quest for ^{5}H has been undertaken in many laboratories, and today the consensus is that a bound ^{5}H does not exist. However, this far, experiments aiming at an identification of ^{5}H have led to contradictory results (see the compilation [5] and Refs. [6–8]).

The main experimental method for the identification of the unbound isotopes in the experiments mentioned above is the missing-mass method combined with an analysis based on deviations of the measured spectra from phase space evaluations. However, this method should be used with caution at low beam energies when many particles in the final state are close in momentum space and thus the phase space may strongly be modified by their final-state interaction.

At high beam energies, the reaction mechanism is much simpler than at low energies. The nucleon knockout channel dominates, and by selecting a structurally close projectile, resonances observed by the method of invariant mass measurement are almost free from background stemming from other reaction mechanisms [9]. Our approach is to use the one-proton knockout reaction from ^{6}He at high bombarding energy and construct the relative energy spectrum in the $t + n + n$ center of mass system (E_{tnn}). The interpretation of the data is done in the framework of an analysis using a restricted set of hyperspherical harmonics (HH) [10,11]. This, in order to obtain the relative weights of the predominant partial waves, and further to assign the spin and parity to the structure seen in the energy spectrum. A detailed account, including discussions on background corrections and misidentified one-neutron events, is presented in [12].

The radioactive ^{6}He beam was produced in a fragmentation reaction of a primary ^{18}O beam (340 MeV$/u$) impinging on a 8 g/cm^{2} Be production target, delivered by the *Schwerionensynchrotron* (SIS) at the *Gesellschaft für Schwerionenforschung mbH* (GSI) in Darmstadt, Germany. The separation of ^{6}He from the reaction products was performed with the fragment separator (FRS) by magnetic rigidity analysis. The secondary ^{6}He beam (240 MeV$/u$) was then directed towards a carbon reaction target (thickness 1.87 g/cm^{2}) situated in front of the large-gap dipole magnet spectrometer ALADIN and the large area neutron detector, LAND [13]. The coincident tritons and neutrons from the reaction were identified and their momenta measured. Details about the setup can be found in Refs. [12,14]. The measured distributions have been corrected for instrumental effects such as restricted acceptance and efficiency. The momentum distributions of the tritons and neutrons and the reconstructed momentum of ^{5}H ($t + n + n$) reveal a peak centered at a value corresponding to the projectile velocity in longitudinal direction. This is an important observation showing that the proton knockout just cut out a proton from ^{6}He with very low momentum transfer to the $t + n + n$ system. The measured momenta of the triton and the neutrons were transformed into the projectile rest frame by using the appropriate relativistic expressions. In this system the longitudinal and transverse widths of the momentum distributions are approximately the same.

The distribution of the total kinetic energy E_{tnn} in the three-body system equivalent of an invariant mass spectrum is shown in Fig. 1. The observed structure exhibits a width of about 6 MeV (FWHM) with a maximum at about 3 MeV.

Two observations are important for the further analysis; (i) The triton and the two neutrons are found to have essentially the velocity of the primary ^{6}He beam, and (ii) the E_{tnn} spectrum shows a structure akin to a resonance. First we discuss possible artifacts that may give a peak structure in E_{tnn}.

(i) The experimental filter.—Instrumental effects due to restricted acceptance or efficiency may have been incorrectly accounted for during the analysis resulting in a distortion of the spectrum. We have therefore in addition to the $t + n + n$ data, also analyzed the $t + n$ events and compared the results with the known ^{4}H results [12]. We find in the energy region of interest here an excellent agreement between the position and width of the ^{4}H resonance with that of previous experiments [5]. The shape of the E_{tnn} spectrum in thus not due to experimental distortions.

(ii) Three-body phase space.—A three-body phase space distribution for ^{5}H decay would have an energy dependence $\sim E^2$. In the energy region of interest here, this would not give a peaklike structure.

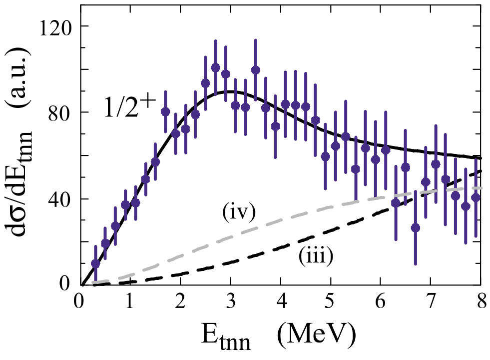

FIG. 1 (color online). Relative energy spectrum of the $t + n + n$ system. The experimental data are shown with statistical uncertainties. The estimated cross section is 30(10) mb. The solid line is the result of a three-body microscopic calculation assuming $I^\pi = 1/2^+$ [2]. The dashed black line (iii) represents an excited ^{6}He resonance and the gray dashed line (iv), a calculation using a realistic ^{6}He wave function from Ref. [15], see text.

(iii) ^{6}He resonance decay.—We have also checked whether an excitation of ^{6}He above the $t + 2n + p$ threshold followed by its decay could mimic this distribution. Note that the decay products from this channel would have longitudinal velocities close to the projectile velocity, similar to the experimental observation. To estimate the shape of a relative energy spectrum from this possible channel we use

$$\frac{dN}{dE_{tnn}} \sim \int_{E_{tnn}}^{E_{\max}} \frac{\Gamma E_{tnn}^2 \sqrt{x - E_{tnn}}}{(E_r + Q - x)^2 + \Gamma^2/4} dx, \qquad (1)$$

where E_r and Γ are the ^{6}He resonance energy and width, respectively. $E_{\max}$ is the available energy in the system. The first resonance above the $t + 2n + p$ threshold in ^{6}He from Ref. [5] ($Q = -20.8$ MeV, $E_r = 23.3$ MeV, $\Gamma = 14.8$ MeV) was used in the calculation. The shape of the calculated distribution is shown in Fig. 1 as a black dashed line (iii). It deviates strongly from the experimental distribution.

(iv) Initial-state effect.—Finally, we checked whether correlations arising solely from the ^{6}He ground-state wave function (i.e., without involving a real ^{5}H resonance), could mimic the observed spectrum. We used the result from Ref. [15] which is shown in Fig. 1 as a gray dashed line (iv). We find that the initial-state correlations are not strong enough to reproduce the experimental spectrum.

The conclusion is that the observed spectrum represents a resonance. However, a conventional analysis using a Breit-Wigner expression is not appropriate to analyze a broad few-body resonance and the maximum observed at 3 MeV cannot be identified with the resonance position in a straightforward way. The spectrum was therefore compared with calculations made within a strict three-body $t + n + n$ dynamics [2], with $I^\pi = 1/2^+$, $E_{\text{res}} =$ 2.5–3.0 MeV, and $\Gamma = 3$–4 MeV. As can be seen in Fig. 1, good agreement is achieved between the experimental data and the calculated distribution with $I^\pi = 1/2^+$, considered to be the ^{5}H ground-state configuration in [2].

To independently confirm the $I^\pi = 1/2^+$ assignment, an analysis of the energy and angular correlations in the $t + n + n$ system was performed as follows.

We introduce a set of normalized Jacobi momentum coordinates:

$$\begin{aligned} \mathbf{q}_{12} &= \left(\frac{\mu_{12}}{2}\right)^{1/2}\left(\frac{\mathbf{p}_1}{m_1} - \frac{\mathbf{p}_2}{m_2}\right); \\ \mathbf{q}_{3-12} &= \left(\frac{\mu_{3-12}}{2}\right)^{1/2}\left(\frac{\mathbf{p}_3}{m_3} - \frac{\mathbf{p}_1 + \mathbf{p}_2}{m_1 + m_2}\right), \end{aligned} \qquad (2)$$

where m_i, μ_{12}, μ_{3-12}, and $\mathbf{p}_i$, ($i = 1, 2, 3$) are masses, reduced masses, and momenta of the particles in the projectile rest frame, respectively. Two different Jacobi coordinates are used, **A** and **B**. In **A** indices 2, 3 are related to neutrons and 1 to the triton, while in **B** 1, 2 are related to the neutrons and 3 the triton. The total kinetic energy in the $t + n + n$ system is then equal to $E_{tnn} = q_{12}^2 + q_{3-12}^2$.

The three-body configuration is then determined by the angle ϑ between the Jacobi momenta $\mathbf{q}_{12}$ and $\mathbf{q}_{3-12}$, by the total energy of the three-body system E_{tnn} and by the energy shared by a pair of particles $\varepsilon = q_{12}^2/E_{tnn}$. Finally, the energy and angular correlations in the $t + n + n$ system can be described by a probability distribution $\mathcal{W}(\varepsilon, \vartheta)$, representing the probability of finding the system in a configuration in vicinity of definite values ε and ϑ.

This distribution was determined from the experimental data and its projections on angular and energy axis in the two different Jacobi coordinates are shown in Fig. 2 where (i) and (iii) are shown in Jacobi configuration **A** ($n - tn$) and, (ii) and (iv) in configuration **B** ($t - nn$). The distribution $\mathcal{W}(\varepsilon, \vartheta)$ was constructed from events restricted to the vicinity of the peak position ($E_{tnn} \sim$ 1–5 MeV) in the ^{5}H relative energy spectrum.

In order to determine the weights of the different partial waves in the $t + n + n$ system from the experimental data, the method proposed in Ref. [11] was used. The method is based on a fitting procedure using the HH series expansion of the amplitudes of the three-body decay.

Fitting the data we used an approximation excluding the core spin and with $K = 0, 2$ and $l_{x(y)} = 0, 1$. These components exhaust 97% of the norm of the ^{6}He ground-state wave function [16]. The expansion is characterized by a set of complex amplitudes $C_{SKl_xl_y}$ for the respective harmonics (namely, C_{0000}, C_{0200}, C_{0211}, and C_{1211}), where S is the total spin of the two neutrons, K the hypermomentum, and $l_{x(y)}$ are the angular momenta connected with the $\mathbf{q}_{12}$ and $\mathbf{q}_{3-12}$ coordinates, respectively. Note, that the antisymmetrization of the wave function with respect to the two neutrons results in $C_{0211} = 0$ in Jacobi system **B**.

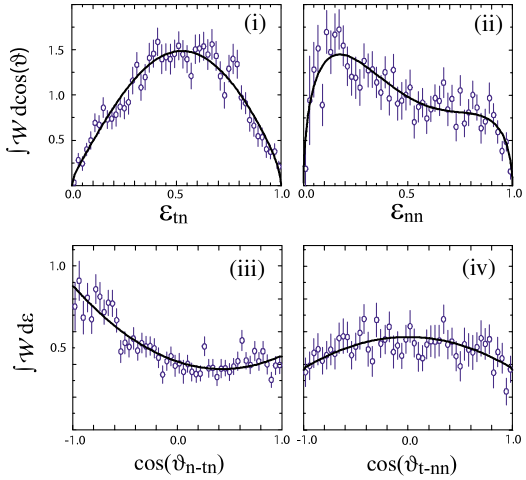

FIG. 2 (color online). Projections of the probability distribution $\mathcal{W}(\varepsilon, \vartheta)$ in two different Jacobi coordinate systems. (i),(iii) are shown in Jacobi configuration **A** ($n - tn$), (ii),(iv) in configuration **B** ($t - nn$). The experimental data are shown with statistical uncertainties. The solid lines represent the fit to the distributions on the basis of HH expansion after convolution with the detector resolution.

The weights of the different partial waves were extracted by simultaneously fitting the four distributions shown in Fig. 2 taking the experimental resolution into account.

The result is shown in Table I, and its correspondence with the experimental data is demonstrated in Fig. 2.

The resulting probability distribution $\mathcal{W}(\varepsilon, \vartheta)$ in Jacobi set **B** without corrections for the experimental resolution is shown in Fig. 3.

The configurations with C_{0000} and C_{0200} directly result in a total spin $I^\pi = 1/2^+$. Some portion of the C_{1211} component can also be assigned to this spin and parity.

From the weights given in Table I, the conclusion is thus that the $I^\pi = 1/2^+$ state in the ^{5}H system is populated with a probability of larger than 63(4)%. Further, a transformation to Jacobi system **A**, provided by Raynal-Revai coefficients [17], results in about 80% probability of a configuration with two neutrons in the p shell [12].

It should be noted that the weight of the configuration with $K = 0$ in ^{5}H is significantly larger than that calculated for ^{6}He. The increase of this component is expected due to the smaller three-body centrifugal barrier determined by K in this decay channel. Further, the increase of the $K = 0$ contribution can be attributed to the n-n interaction in the final state, strongly distinguished in Fig. 2(ii),(iii). The effects of the n-n interaction are well pronounced even though the experimental phase difference β_{0200} results in a decrease of the interference term compared with the ^{6}He calculation. Compared to ^{6}He, the component with $S = 1$ and $K = 2$ is also larger in the experimental ^{5}H data. However, as mentioned above, it cannot be compared in a straightforward way but the difference might be attributed to the $t - n$ final-state interaction.

For jj coupling, the $S = 1$ component, which is directly related to C_{1211}, is to about 33% in the pure $(p_{3/2})^2$ configuration. The transformation of the experimental data from the LS coupling scheme used in the current analysis into the jj coupling scheme remains ambiguous as far as the phase of C_{1211} cannot be determined from the

TABLE I. Weights $|C_{SKl_xl_y}|^2$ of the different partial waves (given in percent), obtained from the experimental data in Jacobi set **B**. The theoretical calculations for the ^{6}He ground-state wave function are from Ref. [16]. The phase differences (β) between C_{0000} and C_{0200} are given in degrees.

Config.	$\vert C_{0000}\vert^2$	$\vert C_{0200}\vert^2$	$\vert C_{1211}\vert^2$	β_{0200}	Reference
^{5}H	18(3)	45(2)	37(4)	61(2)	Pres. exp.
^{6}He	4	78	15	0	[16] theo.

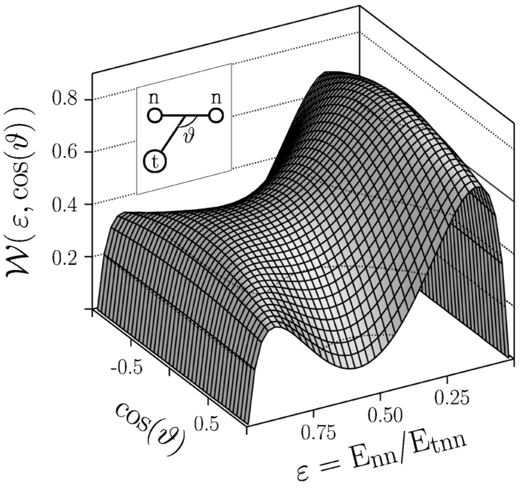

FIG. 3. Two dimensional plot of the probability distribution $\mathcal{W}(\varepsilon, \cos(\vartheta))$, extracted using the series expansion of the final state wave function into the hyperspherical functions with amplitudes adjusted to fit the experimental data. The inset sketches the used coordinate system **B**.

experimental data. A transformation adopting the phase shift from the ^{6}He calculation [16] would result in about 80% of the weight of a configuration with the two neutrons in $p_{3/2}$ shell, and only 1% would be left for a possible $p_{1/2}$-shell admixture.

Thus, a good resemblance between the ^{6}He wave function and the structure of the $t + n + n$ system is found, and the observed differences are qualitatively explained by the decay processes of the preformed ^{5}H.

The probability distribution $\mathcal{W}(\varepsilon, \vartheta)$ shown in Fig. 3 reveals several features which are not seen in the projections in Fig. 2. The angular distributions are almost flat when the relative energy ε between the two neutrons is close either to 0 or to 1. In contrast it behaves almost as $\sin^2\vartheta$ when ε is close to 0.5. This is connected with the fact that the contribution from the $K = 2$, $S = 0$ harmonic is strongly suppressed in this region and the harmonic with $K = 2$, $S = 1$ predominantly determines the correlations. Further, the probability distribution $\mathcal{W}$ along the fractional energy axis (ε) reveals two distinct peaks clearly seen in the vicinity of $\vartheta = 0$ and 180°. The peaks are described mainly by the interference of the harmonics with $K = 2$, $S = 0$ and $K = 0$, $S = 0$ and reflects the dynamical correlations which have been discussed for the ^{6}He wave function in microscopic calculations [16]. In the conjugated spatial coordinates the two measured peaks correspond to the di-neutron configuration with the two neutrons forming a cluster on one side of the triton and to the cigarlike configuration where the neutrons are separated from each other by the triton core.

We conclude the following: The reconstructed ^{5}H spectrum from ^{6}He proton knockout is rather different from the sharp peak reported in Refs. [6,8] but in fair agreement with the results presented in Refs. [7,18]. It is shown that the observed shape cannot be attributed to background processes. Furthermore, it agrees with calculations made within strict three-body $t + n + n$ dynamics [2] assuming an $I^\pi = 1/2^+$ ground state of ^{5}H only. The experimental three-body correlations are analyzed in a model independent way with the result, that the apparent resonance with both neutrons in the p shell has spin and parity $I^\pi = 1/2^+$. Thus its structure resembles that of ^{6}He.

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