Observation of Excited States in ^{5}H

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The ^{5}H system was produced in the ^{3}H$(t, p)^5$H reaction studied with a 58 MeV tritium beam at small c.m. angles. High statistics data were used to reconstruct the energy and angular correlations between the ^{5}H decay fragments. A broad structure in the ^{5}H missing mass spectrum showing up above 2.5 MeV was identified as a mixture of the $3/2^+$ and $5/2^+$ states. The data also present evidence that the $1/2^+$ ground state of ^{5}H is located at about 2 MeV.

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The properties of very asymmetric nuclear matter represent a problem in subatomic physics, being far from understood. The study of the superheavy hydrogen isotopes ^{5}H [1–5] and ^{7}H [6,7] could shed light on this subject. The controversy in the results obtained to date on the ^{5}H system has produced an intense discussion (see, e.g., the review in Ref. [8]) that has appeared even in the popular literature. Essentially, the question is whether the ^{5}H ground state (g.s.) is located at 1.7–1.8 MeV above the $t + 2n$ decay threshold [2,3], or at about 3 MeV [4] or even higher [1,5]. Theory papers [9–15] also give diverse predictions here. Consequently, new experiments must be carried out if this important question is to be resolved.

In the present work we studied the same ^{3}H$(t, p)^5$H reaction as in Ref. [3] but in a different kinematical region. Because of the kinematic focusing, the ^{5}H decay products $(t + 2n)$ were detected almost in the whole angular range. The high statistics collected allowed a detailed study of correlations between the decay products so that it was possible to identify a broad structure lying above 2.5 MeV in the missing mass spectrum of ^{5}H as a mixture of $3/2^+$ and $5/2^+$ states. Evidence can be found in the correlation data that the g.s. of ^{5}H is located at about 2 MeV. Thus, our results support the experimental observations of Refs. [2,3]. There is also a qualitative agreement with theoretical calculations predicting an energy split of 1.5–3 MeV between the g.s. and the first excited state of ^{5}H [9–11,14].

Experiment.—A 58 MeV triton beam was produced at the U-400M cyclotron of FLNR JINR (Dubna, Russia). The ACCULINNA separator [16] was used to reduce the angular spread and energy dispersion of the primary triton beam to 7 mrad and 0.3 MeV (FWHM), respectively. Finally, the triton beam with intensity of 3×10^7 s^{-1} was focused in a 5 mm spot on a cryogenic tritium target [17]. The 4 mm thick target cell was filled with tritium to a pressure of 860 mbar and cooled down to 25° K.

The experimental setup is shown in Fig. 1. Slow protons emitted in the backward direction from the target were measured by an annular 300 μm Si detector with an active area covering a ring with inner and outer diameters of 32 and 85 mm, respectively. The detector was installed 100 mm upstream of the target. It was segmented in 32 rings on one side and 32 sectors on the other side, thus ensuring good position resolution. The detection threshold for protons was 1 MeV. Charged particles mov-

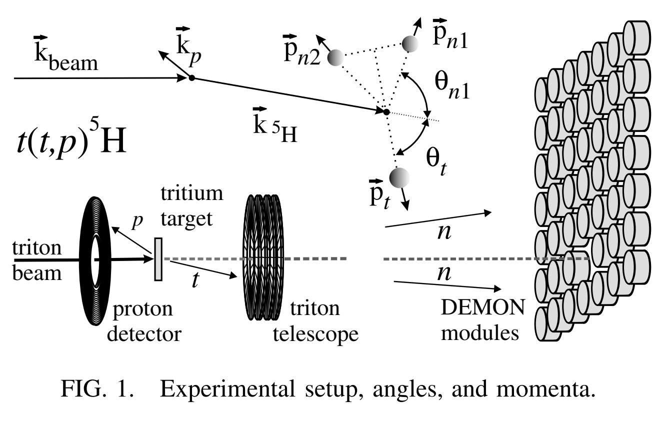

FIG. 1. Experimental setup, angles, and momenta.

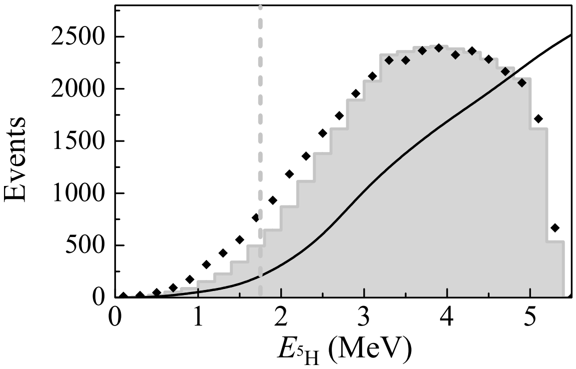

FIG. 2. Missing mass spectrum of ^{5}H. The vertical dashed line shows the position of the ground state deduced in Refs. [2,3]. Diamonds show the data, the histogram filled in gray is the result of MC simulation, and the solid curve is the input for MC simulation. Here and below, the data points show the real numbers of detected events.

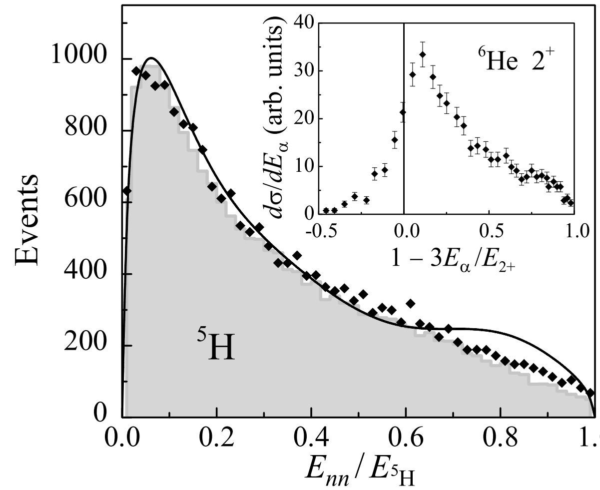

FIG. 3. Relative energy spectrum for two neutrons. The plot details are the same as in Fig. 2. The inset shows the inclusive α spectrum from the decay of the ^{6}He 2^+ state [26].

ing in the forward direction were detected by a telescope consisting of four annular Si detectors of the same radii as the one used to detect protons. The thicknesses of these detectors were 300 μm and 3×1 mm. The two sides of the first, 300 μm detector, were segmented in 16 rings and 16 sectors. In two different runs this telescope was installed at a distance of either 150 or 220 mm from the target cell. Neutrons were detected by 48 scintillation modules of the time-of-flight spectrometer DEMON [18]. Being installed at a distance of 2.5 m from the target the modules covered an angular range of $\theta_{\mathrm{lab}} = 5°$–$40°$.

Data analysis and discussion.—In this Letter we present only the results for triple *ptn* coincidence events. Such events uniquely identify the $p + {}^5$H outgoing channel and make possible a complete kinematic reconstruction. Data in the center-of-mass (c.m.) system of ^{5}H$(t + 2n)$ are shown by diamonds in Figs. 2–4. The direction of the momentum transfer $\mathbf{k}_{\mathrm{beam}} - \mathbf{k}_p$ occurring in the reaction ^{3}H$(t, p)^5$H was chosen as the z axis (see Fig. 1 for notations). The ^{5}H missing mass spectrum is shown in Fig. 2. We have measured this spectrum up to 5 MeV with good efficiency. The 5.5 MeV limit is caused by the detection threshold for slow protons moving in the backward direction. Figure 3 shows the distribution of the ^{5}H decay energy ($E_{^5\mathrm{H}}$) between the relative motions in the $t - nn$ and nn subsystems (presented in terms of the $E_{nn}/E_{^5\mathrm{H}}$ ratio). It shows a narrow peak corresponding to a strong "dineutron" final state interaction.

The most striking result is the observation of a sharp oscillating picture in the triton angular distribution shown in Fig. 4. Such correlations can be obtained only for very specific conditions. Some comments on correlations occurring in transfer reactions are appropriate here.

(a) An oscillating picture in the angular distribution can be observed for the decay products of a resonance state in the conditions of "zero degree geometry" (in a sequential process the first particle is emitted at zero degree). This happens if the resonance is populated in a reaction with spinless particles, and the decay products also have zero spins [29]. A typical example is the case of $\alpha_1 - \alpha_2$ angular correlations observed in the reaction ^{16}O$(^{12}$C$, \alpha_1(0°))^{24}$Mg$^*(\alpha_2(\theta))^{20}Ne_{\mathrm{g.s.}}$ (e.g. Ref. [19]).

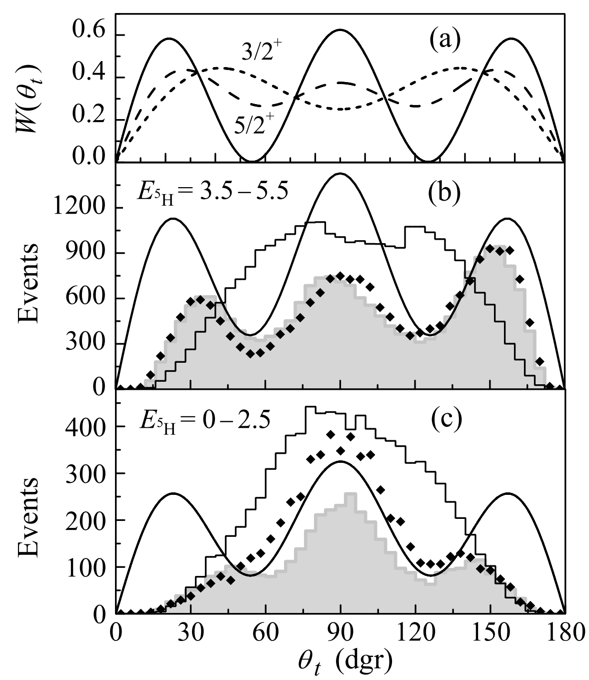

FIG. 4. Panel (a) shows the spin degeneracy case (solid curve, pure $|P_2^0|^2$) and correlations obtained by the population of isolated $5/2^+$ (dashed curve) and $3/2^+$ (dotted curve) states. Here only the $l_x = 0$, $l_y = 2$ amplitude in ^{5}H is included. Panels (b) and (c) give the angular distributions of tritons in the ^{5}H frame for the two ranges of the ^{5}H energy. Spin alignment is maximal (the minimal magnetic substates are populated) in all the cases. The plot details here are the same as in Fig. 2. Solid histogram is MC simulation of isotropic distribution.

(b) The oscillating picture is also observed in reactions where particles with nonzero spin are involved, like the $d-\alpha$ angular correlation in the $^{12}C(^6Li, d)^{16}O^*(\alpha)^{12}C_{g.s.}$ reaction [20]. In this case only the direct α particle transfer makes it possible, and, again, only spinless nuclei participate in the formation and decay of the resonance [30].

(c) To our knowledge, only one observation of an oscillating pattern was reported for the reaction involving a spin 1/2 nucleus: $^{13}C(^6Li, d)^{17}O^*(\alpha)^{13}C_{g.s.}$ [21]. It was shown in Ref. [22] that the energy degeneracy and interference of (at least) two states are required to reproduce the observed correlations.

Very interesting, although not completely relevant to our situation, are the high energy nuclear excitation studies of the ^{6}He 2^+ state [23], where the oscillating picture of angular distribution has also been observed.

Figure 4(a) shows that the strongly oscillating distribution can not be obtained for ^{5}H assuming the population of one selected J^π. This figure gives the result obtained that best describes the oscillations; that is, the complete spin alignment and population of one $\{L = 2, S_x = 0, l_x = 0, l_y = 2\}$ component in ^{5}H (L is the total angular momentum, subscripts x and y refer to the spins and angular momenta of nn and $t-nn$ subsystems).

Keeping in mind the discussion given above, then the bulk of data observed in the present experiment can be explained by the assumption that the direct transfer of two neutrons ($\Delta L = 2$, $\Delta S = 0$) dominates in the $^3H(t, p)^5H$ reaction leading to the population of the broad, overlapping $3/2^+$ and $5/2^+$ states. The idea is supported by the following arguments.

(i) The ^{5}H system could be considered as a "proton hole" in ^{6}He (e.g., [11]), so definite similarities can be expected between these systems. Theoretical predictions give $J^\pi = 1/2^+$ for the ground state of ^{5}H. The low lying excited states are supposed to be a $3/2^+$ and $5/2^+$ doublet. One should expect a weak population of the ^{5}H g.s. in the $^3H(t, p)^5H$ reaction due to the statistical factor and also as a consequence of the "angular momentum mismatch" that arises from the fact that the light proton can not carry away as much angular momentum as the heavier triton projectile brings in. Distorted wave Born approximation calculations confirm this idea indicating that the momentum transfers $\Delta L = 1, 2$ dominate, whereas $\Delta L = 0$ is suppressed by about 1 order of magnitude even at forward angles.

(ii) The spin transfer is negligible in this reaction. $\Delta S = 1$ is possible only if the two neutrons are in a negative parity state of relative motion. The previous experience shows that this is highly improbable in contrast to the dineutron transfer, which is known to be a good approximation valid in a broad range of transfer reactions.

(iii) The $3/2^+$ and $5/2^+$ states can be considered as degenerate. Theory calculations (e.g., [11]) show that the expected energy split between these states is much less than their widths.

(iv) To produce the strongly oscillating picture, the domination of the $\{L = 2, S_x = 0, l_x = 0, l_y = 2\}$ component in the ^{5}H wave function is necessary. This is a reasonable expectation supported both by the analysis of experimental data [24] and theoretical calculations [25] made for the ^{6}He 2^+ state (we have mentioned the expected similarities between ^{5}H and ^{6}He). The decay amplitudes deduced for the ^{6}He 2^+ state (Table I) and corresponding α spectrum (inset in Fig. 3) confirm this idea.

We employed the following procedure for data analysis. Correlations occurring at the ^{5}H decay are described as

$$W = \sum_{JM,J'M'} \langle J'M'|\rho|JM\rangle A^\dagger_{J'M'} A_{JM},$$

where J, M are the total ^{5}H spin and its projection, A_{JM} are the decay amplitudes depending on the ^{5}H decay dynamics. $\langle J'M'|\rho|JM\rangle$ is the density matrix, which describes the polarization of the ^{5}H states populated in the $^3H(t, p)$ reaction and takes into account the mixing of the $3/2^+$ and $5/2^+$ states. It was parameterized assuming azimuthal symmetry with respect to the momentum transfer in the $^3H(t, p)$ reaction. This assumption is well confirmed by the experimental data and reduces to five the number of independent parameters. All elements of the density matrix were assumed to have the same energy dependence and were represented by splines. The amplitudes A_{JM} were expanded over a limited set of hyperspherical harmonics (assumed to be the same for the $3/2^+$ and $5/2^+$ states). A similar approach has been used in Ref. [27], where the nonisotropic three-particle decay of $^6Be(2^+)$ state has been explored. The hyperspherical expansions of the decay amplitudes were also used for the analysis of $A = 6$ [24,28] and ^{5}H [4,8] decay data.

Parameters of the ρ-matrix and hyperspherical expansion were treated as free in our analysis. A complete Monte Carlo (MC) simulation of the experiment has been performed. In this way analytical expressions were extracted for the decay probability in the multidimensional space, corrected for the setup efficiency. Projections of the extracted distributions (solid curves) and the results of MC

TABLE I. Hyperspherical decompositions of decay amplitudes A_{JM} for the excited states of ^{5}H ($E_{^5H} = 2.5$–5.5 MeV) and ^{6}He (the squared moduli of the partial amplitudes are given in percent and relative arguments in degrees). The two variants of the analysis for ^{6}He from [24] are presented as it appeared to be insensitive to the weight of the $S_x = 1$ component. The errors given for our fit are purely statistical; the other possible uncertainties are discussed in Ref. [24].

					^{6}He2+ [24,26]				^{5}H	
K	L	l_x	l_y	S_x	mod^2	arg	mod^2	arg	mod^2	arg
2	2	0	2	0	62	0	49	0	35(2)	0
4	2	0	2	0	25(6)	120(10)	15(5)	140(10)	37(2)	58(1)
6	2	0	2	0					8(1.5)	138(6)
2	2	2	0	0	13(2)		11(1.5)		20(2)	180(3)
2	1,2	1	1	1			25		0(3)	

simulations (gray histograms) are shown in Figs. 2–4 together with the experimental data. The hyperspherical amplitudes are listed in Table I together with the amplitudes extracted in Ref. [24] from the ^{6}He 2^+ decay data [26].

Agreement obtained between the data and the MC results is excellent at $E_{^5\mathrm{H}} > 2.5$ MeV [Fig. 4(b)]. Below this energy, we could not achieve an agreement assuming the interference of only $3/2^+$ and $5/2^+$ states. This can be well seen in Fig. 4(c). The impact of this disagreement on the ^{5}H missing mass spectrum is also reflected in Fig. 2 in the deviation of the MC results from the experimental data below 3 MeV [31]. We can reproduce the correlations obtained at $E_{^5\mathrm{H}} < 2.5$ MeV by assuming the interference of the $1/2^+$ ground state with the $3/2^+$–$5/2^+$ doublet. One can take this as an evidence for the population of the ^{5}H g.s. lying at about 2 MeV.

Interference of the $1/2^+$, $3/2^+$, and $5/2^+$ states becomes possible in the ^{5}H missing mass spectrum when the detection probability of the ^{5}H decay fragments depends on their emission angles. This dependence was strongly pronounced in Ref. [3] and had a place in this Letter. Interference was considered in Ref. [3] as a possible explanation for the too small width of the ^{5}H peak observed at 1.8 MeV. The interference of the ^{5}H ground state with the $3/2^+$–$5/2^+$ doublet, apparently showing up in the correlation patterns observed in the present work at $E_{^5\mathrm{H}} <$ 2.5 MeV, supports this assumption of Ref. [3]. The possible narrow peak at 2.7 MeV discussed in [3] is not confirmed in this Letter.

Conclusion.—The missing mass spectrum of ^{5}H obtained in this Letter shows a broad structure above 2.5 MeV. The observed strong correlation pattern allows us to unambiguously identify this structure as a mixture of the $3/2^+$ and $5/2^+$ states. Such a correlation is a rare phenomenon for transfer reactions involving particles with nonzero spin and means that the $3/2^+$ and $5/2^+$ states are either almost degenerate or the reaction mechanism causes a very specific interference of these states.

The observation of excited states in this energy range imposes an upper limit on the energy of the ^{5}H g.s. resonance and is in a good agreement with the experimental observations of Ref. [2], finding the ^{5}H g.s. at 1.7 MeV. The correlation picture at $E_{^5\mathrm{H}} < 2.5$ MeV gives additional evidence for the interference of the $3/2^+$–$5/2^+$ doublet with the ground $1/2^+$ state in ^{5}H and is consistent with the alternative explanation presented in Ref. [3] for the small width of the 1.8 MeV g.s. peak of ^{5}H.

The analysis of angular and internal energy correlations for ^{5}H shows a reasonable agreement of the deduced structure of ^{5}H with the one calculated or deduced from experimental data in the case of the ^{6}He 2^+ state.

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[1] D. V. Aleksandrov *et al.*, *Proc. Int. Conf. on Exotic Nucl. and At. Masses, Arles, France, June 19–23, 1995*, (Editions Frontieres, Gif-sur-Yvette, 1995), p. 329.
[2] A. A. Korsheninnikov *et al.*, Phys. Rev. Lett. **87**, 092501 (2001).
[3] M. Golovkov *et al.*, Phys. Lett. B **566**, 70 (2003).
[4] M. Meister *et al.*, Nucl. Phys. A **723**, 13 (2003); Phys. Rev. Lett. **91**, 162504 (2003).
[5] M. G. Gornov *et al.*, JETP Lett. **77**, 344 (2003).
[6] A. A. Korsheninnikov *et al.*, Phys. Rev. Lett. **90**, 082501 (2003).
[7] M. Golovkov *et al.*, Phys. Lett. B **588**, 163 (2004).
[8] L. V. Grigorenko, Eur. Phys. J. A **20**, 419 (2004).
[9] J. J. Bevelacqua, Nucl. Phys. A **357**, 126 (1981).
[10] N. A. F. M. Poppelier, L. D. Wood, and P. W. M. Glaudemans, Phys. Lett. B **157**, 120 (1985).
[11] N. B. Shul'gina *et al.*, Phys. Rev. C **62**, 014312 (2000).
[12] P. Descouvemont and A. Kharbach, Phys. Rev. C **63**, 027001 (2001).
[13] N. K. Timofeyuk, Phys. Rev. C **65**, 064306 (2002).
[14] K. Arai, Phys. Rev. C **68**, 034303 (2003).
[15] L. V. Grigorenko, N. K. Timofeyuk, and M. V. Zhukov, Eur. Phys. J. A **19**, 187 (2004).
[16] A. M. Rodin *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. B **126**, 236 (1997).
[17] A. A. Yukhimchuk *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **513**, 439 (2003).
[18] I. Tilquin *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **365**, 446 (1995).
[19] L. K. Fifield *et al.*, Phys. Rev. C **8**, 2217 (1973).
[20] K. P. Artemov *et al.*, Sov. J. Nucl. Phys. **22**, 125 (1976).
[21] K. P. Artemov *et al.*, Sov. J. Nucl. Phys. **28**, 145 (1978).
[22] G. Cardella *et al.*, Phys. Rev. C **36**, 2403 (1987).
[23] D. V. Aleksandrov *et al.*, Nucl. Phys. A **669**, 51 (2000).
[24] B. V. Danilin *et al.*, Yad. Fiz. **46**, 427 (1987).
[25] B. V. Danilin *et al.*, Nucl. Phys. A **632**, 383 (1998).
[26] O. V. Bochkarev *et al.*, JETP Lett. **42**, 374 (1985).
[27] O. V. Bochkarev *et al.*, Sov. J. Nucl. Phys. **55**, 955 (1992).
[28] O. V. Bochkarev *et al.*, Nucl. Phys. A **505**, 215 (1989).
[29] This is a common method for spin assignment. In this case, the decay of the resonance is described by a Legendre polynomial $|P_L(\theta)|^2$, generating $L + 1$ sharp peaks in the angular distribution.
[30] Here, a squared polynomial distribution is observed relative to the direction of the momentum transfer in the ^{12}C(^{6}Li, d)^{16}O reaction [20].
[31] The energy dependence of the ^{5}H spectrum in Fig. 2 is normalized to reproduce the angular distributions observed for tritons at forward and backward angles, see Fig. 4(b) and 4(c).