^{4}H nucleus and the ^{2}H(t, tp)n reaction

S. Blagus, Đ. Miljanić, and M. Zadro
Ruđer Bošković Institute, Zagreb, Yugoslavia

G. Calvi, M. Lattuada, F. Riggi, and C. Spitaleri
Istituto Nazionale di Fisica Nucleare, Catania, Italy and Universitá di Catania, Catania, Italy

C. Blyth and O. Karban
School of Physics and Space Research, University of Birmingham, Birmingham, England

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The ^{2}H(t,tp)n reaction was investigated in a kinematically complete experiment with a tritium beam at energies around 35 MeV. Evidence was found for the ^{4}H ground state. Coincidence spectra were fitted by the contribution of quasifree processes, sequential decay through the ^{4}He ground state, and the n-p final-state interaction. The best agreement with the data was obtained assuming the following ^{4}H ground-state parameters: $E_r=3.1$ MeV and $\gamma^2=2.3$ MeV.

Studies of multiparticle nuclear reactions provide valuable information on reaction mechanism and properties of nuclear structure. Particle unstable light nuclei have received much attention in recent years since the understanding of their properties could give new insights about these systems and the role of three-body forces in nucleon-nucleon interaction.

The $A=4$ system plays a special role in nuclear physics, since it is the lightest few-nucleon system to exhibit excited states [1]. The only known particle stable state is the ^{4}He ground state. Enough evidence has been now accumulated showing that ^{4}H and ^{4}Li have only broad particle unstable states. The data concerning the positions and widths of these states are, however, contradictory.

In the case of ^{4}H several experiments were carried out to extract information concerned with the ground state [2–10]. No firm evidence for ^{4}H excited states exists, even though in some experiments these were claimed to be observed.

Kinematically complete experiments involving few-nucleon systems are appropriate to study ^{4}H properties. One of these reactions is the ^{3}H+^{2}H process, which gives various exit few-body channels. This reaction was already studied with the aim of looking for quasifree processes [11]. Although contributions from ^{4}H states were observed, no details were given about the ground-state parameters. The broad peaks were also observed in proton and deuteron inclusive spectra from the ^{2}H(t,p) and ^{3}H(t,d) reactions, but no analysis was done [12]. For this reason this reaction was reconsidered with the aim to get more information about ^{4}H states by a consistent analysis of the different reaction mechanisms involved. Results from this experiment concerning mainly the quasifree reactions have been recently reported [13,14].

The experiment was carried out at the N.S.F. Tandem Laboratory in Daresbury. A ^{3}H beam at energies of 30 and 35.5 MeV was used to bombard deuterated polyethylene foils with thickness around 2 mg/cm^2. The beam current ranged between 25 and 100 nA. The outgoing charged particles were identified by four solid-state telescopes, each telescope consisting of a 70–100-μm ΔE detector and a 5-mm-thick Si(Li) E detector. Collimation of the telescopes was achieved by rectangular tantalum slits (2×8 mm at a distance of 200 mm from the target). One telescope was put on one side of the beam (arm 1), while the other three, separated by 10°, were on the other side (arm 2). The two arms could be moved independently, thus allowing different combinations of angles to be obtained. A coincidence between any pair of ΔE detectors as well as a prescaled single output from each telescope generated the event trigger for the acquisition. The analog-to-digital-convertor information from each detector together with the time-to-amplitude convertors (TAC's) and a bit-pattern register to label each event were stored event by event for later analysis.

The different charged particles from the ^{3}H+^{2}H reactions were identified in the ΔE-E spectra, and selected particle-particle coincidences for each pair of telescopes were sorted into $(E_1+\Delta E_1)-(E_2+\Delta E_2)$ matrices by choosing windows on the corresponding bit-pattern and relevant TAC spectrum.

The energy calibration was obtained using the ^{3}H+^{2}H and ^{3}H+^{12}C two-body reactions. Absolute cross sections were extracted from the measured target thickness, detector solid angles, and integrated beam current. Checks were made during the experiment to control target deterioration.

Proton-triton coincidences from the ^{2}H(t,tp)n reaction were selected to look for resonances in the n-t relative energy spectra, corresponding to ^{4}H states. The events of interest in the two-dimensional matrices were projected on one of the energy axes, after putting windows on the upper and lower branches of the kinematical locus.

Coincident p-t energy spectra were measured at 35.5

and 30 MeV incident energy, for several pairs of angles. In most of them evidence was found for structures corresponding to the ground state of ^{4}H. Figures 1–3 show some of the obtained spectra.

The three-body phase-space contribution (curves denoted by PS) to the coincidence cross section was preliminarily evaluated and compared to the measured spectra. This showed that the observed structures could not be fitted by this contribution, thus requiring the intervention of quasifree (QF) processes and/or the sequential break-up. The contribution from these mechanisms, together with that arising from the n-p final-state interaction (FSI) was taken into account in the following analysis.

The QF contribution to the cross section proceeds through the QF scattering $t+p \rightarrow t+p$ and the QF reaction $d+d \rightarrow p+t$, where a neutron is left as a spectator

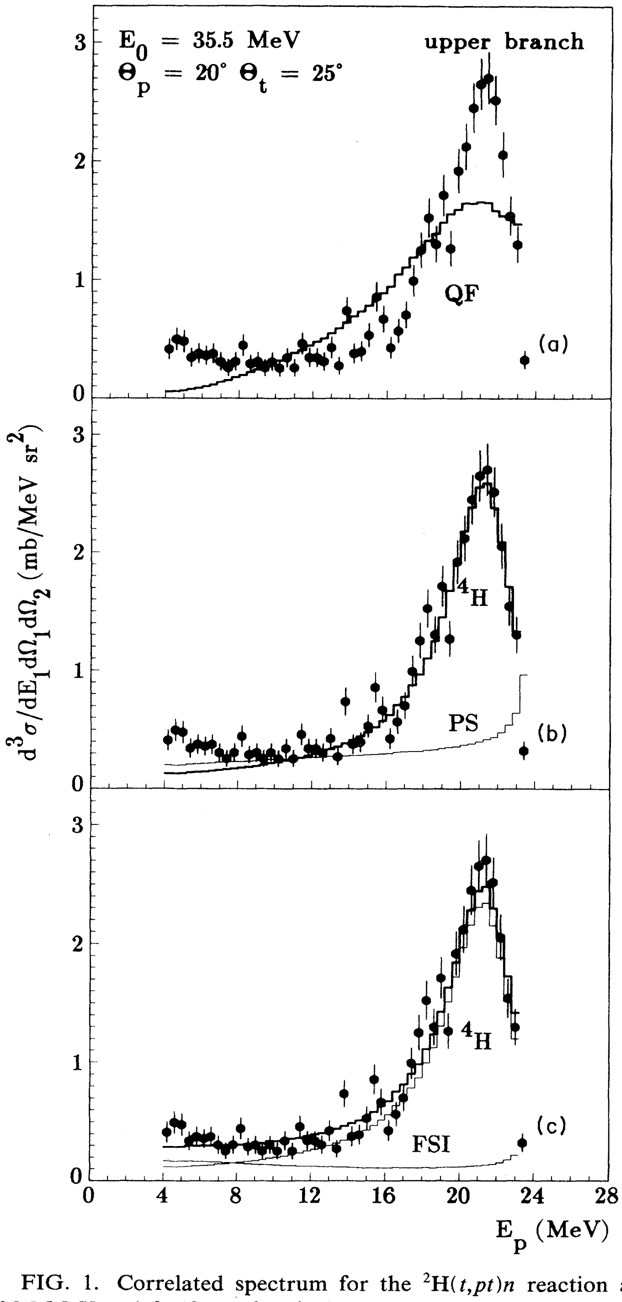

FIG. 1. Correlated spectrum for the ^{2}H(t,pt)n reaction at 35.5 MeV and $\theta_p/\theta_t = 20°/25°$, shown as projection on the proton energy axis. The events around the upper branch of the kinematical locus were projected. The data are compared with the result of different calculations reported as histograms: (a) QF process, described in the PWIA (see text). (b) ^{4}H ground-state sequential decay, and phase-space factor (PS). (c) Incoherent sum of QF contribution, ^{4}H (g.s.) sequential decay, and n-p final-state interaction.

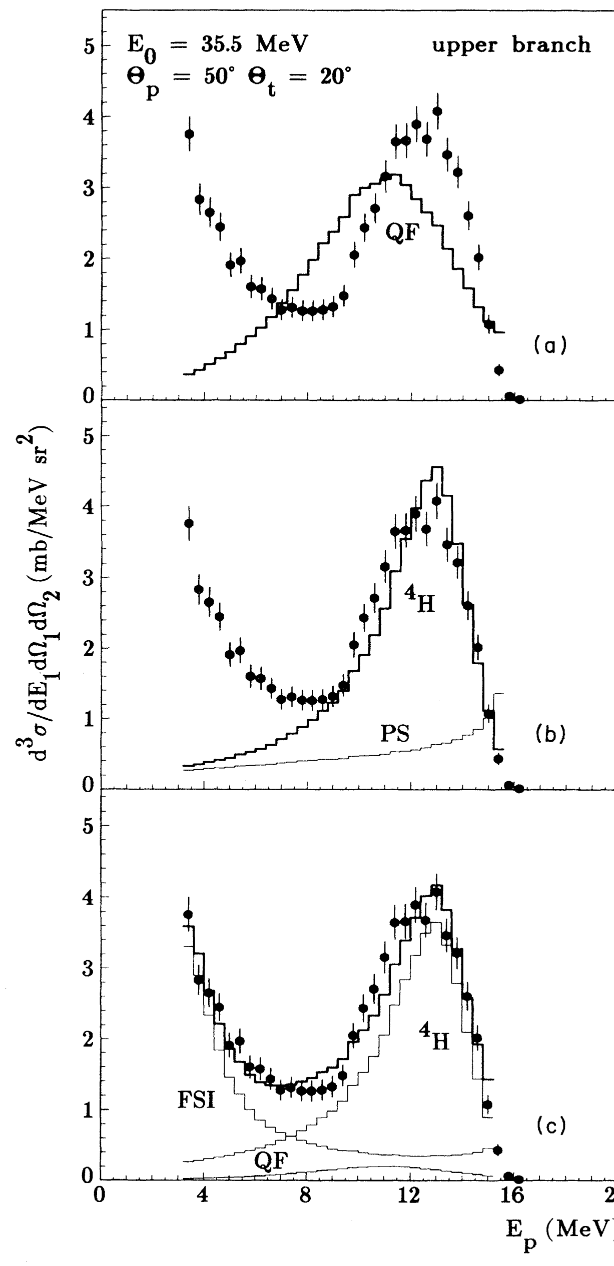

FIG. 2. As in Fig. 1, for $\theta_p/\theta_t = 50°/20°$. The events around the upper branch of the kinematical locus were projected.

in the target or in the projectile, respectively. To evaluate the QF contribution, the plane-wave impulse approximation (PWIA) was used [15]. According to the PWIA, the cross section is written as

$$\left[\frac{d^3\sigma}{d\Omega_1 d\Omega_2 dE_1}\right]=P(\mathrm{KF})\left[\frac{d\sigma}{d\Omega}\right]|\Phi(p_s)|^2 ,$$

where $\Phi(p_s)$ is the Fourier transform of the neutron wave function in the projectile or target nucleus, $(d\sigma/d\Omega)$ is the off-shell two-body cross section for the relevant virtual process, (KF) is a kinematical factor, and P is related to the absolute normalization of the cross section.

The neutron-proton and neutron-deuteron wave functions of ^{2}H and ^{3}H were assumed to be

$$u(r)\sim\frac{e^{-gr}-e^{-br}}{r}$$

with $g=0.4478$ fm^{-1} and $b=1.202$ fm^{-1} for ^{3}H, and $g=0.2317$ fm^{-1} and $b=1.202$ fm^{-1} for ^{2}H [15].

The two-body cross sections were taken from the literature at energies corresponding to the final energy prescription [16].

Figures 1(a), 2(a), and 3(a) show the result of the fit to the experimental spectra through the PWIA contribution only, arbitrarily normalized to the data. The result of the fit includes experimental effects such as finite angular openings of the detectors and energy resolution.

As it can be seen the QF contribution cannot reproduce the shape of the measured spectra, its position being also shifted with respect to the observed peak. A similar result was obtained also for the other spectra (not reported).

The observed structures were then fitted by assuming a sequential decay contribution with formation of the ^{4}H ground state. The cross section for the sequential decay was calculated using a resonance form [5,7]

$$f(E_{nt})=\frac{P_c\gamma^4}{[(E_{nt}-E_r)^2+(P_c\gamma^2)]^2} ,$$

where P_c is the penetration factor, E_r the resonance energy, and γ^2 the reduced width. An interaction radius of 4 fm was assumed to evaluate P_c. Different values of E_r and γ^2 were tried in the analysis and the best agreement with the data was obtained for $E_r=3.1$ MeV and $\gamma^2=2.3$ MeV. Also in this case the experimental effects were included in the calculation. The result is shown in Figs. 1(b), 2(b), and 3(b). A reasonable agreement is obtained showing that the ^{4}H ground state represents a relevant component of the measured cross section.

The n-p final-state-interaction (FSI) contribution was also included. It was calculated by the Watson and Migdal approach [15,17,18]. The excitation energies of ^{4}He in the region of interest (high-energy proton peak) are larger than 25 MeV. At these energies the ^{4}He states are not well known and their contribution was not included in the present calculations.

All the allowed contributions as outlined above and added incoherently, were included in a further fit after folding in the experimental effects. Only the relative weights were treated as free parameters during this fitting and the overall result is shown in Figs. 1(c), 2(c), and 3(c). The data are fairly well reproduced by the calculations, providing further evidence for the contribution of the ^{4}H ground state.

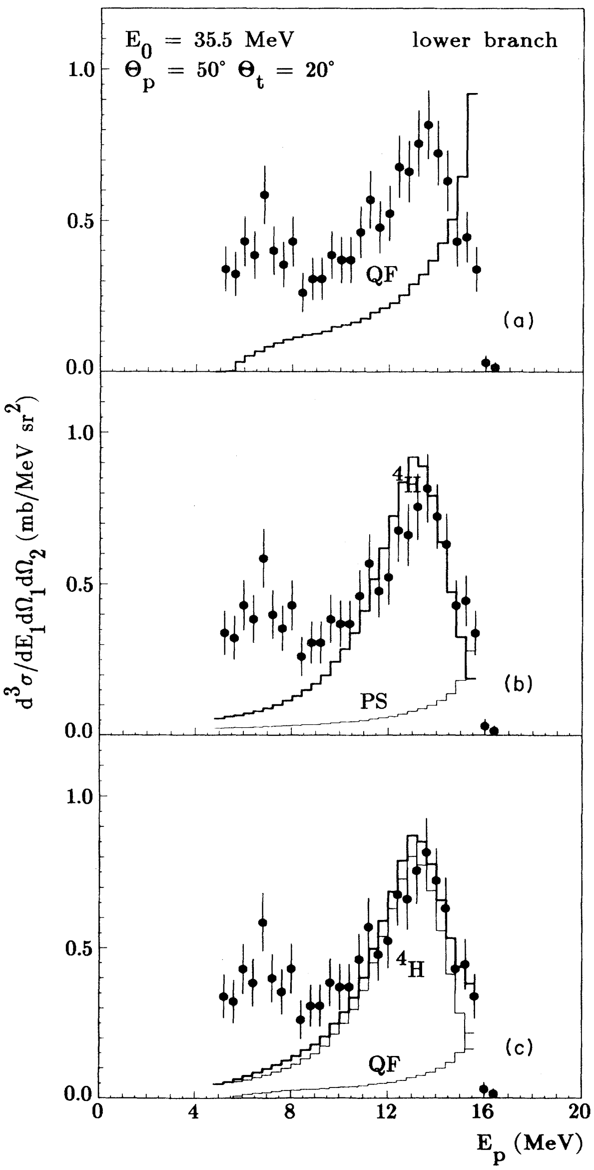

FIG. 3. As in Fig. 1, for $\theta_p/\theta_t=50°/20°$. The events around the lower branch of the locus were projected.

Table I presents the results on ^{4}H ground-state parameters obtained from different experiments. It is seen that the data, except for the oldest π^--^{7}Li experiment, agree well, when one takes into account experimental difficulties.

It is hoped that a complete analysis of all data from the

TABLE I. ^{4}H ground-state parameters as obtained from the experiments.

Reaction	E_i (MeV)	E_r (MeV)	Γ (MeV)	Ref.
^{3}H$(n,n)^3$H	0.06–80	2.6^a	4.5^b	[4]
^{2}H$(t,pt)n$	35.5	3.1±0.3	2.3^c	Present result
^{6}Li$(\pi^-,d)tn$	0	3.6±0.6	3.1±0.7	[10]
^{7}Li$(\pi^-,t)tn$	0	3.8±0.3	3.4±0.8	[10]
^{7}Li$(\pi^-,tt)n$	0	8 ±3	≤4	[3]
^{7}Li$(\pi^-,tt)n$	0	2.7±0.6	2.3±0.6^c	[5]
^{6}Li$(\pi^-,dt)n$	0	2.7	—	[5]
^{7}Li$(n,\alpha t)n$	14.6	2.6 ±0.4	2.1±0.3^c	[7]
^{9}Be$(\pi^-,dt)tn$	0	3.0±0.2	4.7±1.0	[9]
^{7}Li$(^3He,^3$He^{3}He$)tn$	120	2.6±0.2	—	[6]
^{6}Li$(^6$Li$,^8$B$)tn$	93.3	—	—	[2]
^{9}Be$(^{11}$B$,^{16}$O$)tn$	88	3.5±0.5	1	[8]

^{a}Energy in n-t system where total cross section has maximum value.
^{b}Estimated FWHM.
$^c\gamma^2$-reduced width.

present experiment will allow us to draw definite conclusions about the ^{4}H states, thus permitting a comparison with the information recently extracted on ^{4}Li and ^{4}He nuclei [19,20].

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