Search for resonances in ^{4}n, ^{7}H and ^{9}He via transfer reactions

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Abstract.
Investigation of unbound nuclear systems ^{9}He, ^{7}H and ^{4}n was performed at GANIL-SPIRAL using the ^{8}He beam at 15.3 A MeV and a CD_2 target. The missing mass spectra were deduced from kinetic energies and emission angles of light ejectiles detected by the Silicon array MUST. In addition to previously known low-lying narrow resonant states in ^{9}He, the d(^{8}He,p) reaction displays a structure just above neutron emission threshold, identified with the "true" ground state of ^{9}He. The analysis of angular distributions shows that the inversion of $s_{1/2}$ and $p_{1/2}$ neutron shells previously observed in ^{11}Be and ^{10}Li also exists in the lightest N=7 isotone ^{9}He. The d(^{8}He,^{3}He) and d(^{8}He,^{6}Li) reactions were used to search for resonant states in the t+4n (^{7}H) and 4n systems, respectively. The missing mass spectrum of the 4n system does not give evidence for the existence of a bound "tetraneutron". However the comparison with the results of 5-body phase-space calculations emphasizes the existence of correlations in the 4n system. The broad structure observed at $\simeq$2 MeV above the t+4n emission threshold is proposed to be the ground state of ^{7}H.

Keywords: tetraneutron, ^{7}H, ^{9}He, transfer reactions with RNB
PACS: 27.20.+n, 25.60.Je, 21.10.Hw

INTRODUCTION

Properties of very light nuclei can now be predicted by *ab-initio* calculations using available models for nuclear forces. Search for resonant states in few-body systems with a very large N/Z ratio (also including eventual multineutron clusters with Z=0) is

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CP912, *International Symposium on Exotic Nuclei*, edited by Yu. E. Penionzhkevich and E. A. Cherepanov

therefore a matter of particular interest, as their experimental properties can put strong constraints on the poorly known parameters of the neutron-neutron and 3- and 4-body interactions.

The possible existence of multineutron clusters is an old and stimulating topic in both experimental and theoretical Nuclear Physics. On the basis of the analysis of ^{14}Be breakup, it has been suggested [1] that the 4n system could be bound. A different approach has been used in the present work: the investigation of the α-transfer reaction ^{8}He(d,^{6}Li)4n in inverse kinematics, which allows one to search for bound and unbound states in the 4n system via missing mass measurements. The experiment was performed using the secondary beam of ^{8}He from Ganil-Spiral and the light-charged particle detector MUST[2]. Preliminary results were reported in ref.[3]. The same technique was also applied to the investigation of the very exotic unbound nuclei ^{7}H and ^{9}He. These nuclear systems with extremely large neutron-proton asymmetry (N/Z=3.5 and 6 for ^{9}He and ^{7}H, respectively) were produced via the one-nucleon transfer reactions (d,^{3}He) and (d,p) induced by ^{8}He. The present paper reports new results about "tetraneutron" obtained with increased statistics, together with important information about the structure of ^{9}He and the existence of a resonant state in the ^{7}H system.

EXPERIMENTAL TECHNIQUE

The experiments were performed at the GANIL-SPIRAL radioactive beam facility. The ^{8}He incident particles were produced by fragmentation of a ^{13}C beam at 75 A MeV in a thick carbon target and ionized by an ECR source. The secondary beam accelerated by the cyclotron CIME up to the energy of 15.3 A MeV was focussed onto a 99.9% isotopically enriched deuterated polypropylene $(CD_2)^n$ target . The tracking of ^{8}He beam was achieved by two position sensitive gas detectors CATS[4] placed upstream. The maximum intensity of ^{8}He available on target was $\approx$ 1.5 10^4 pps.

The three unbound nuclear systems under investigation were produced by transfer reactions, namely (d,p), (d,^{3}He) and (d,^{6}Li) in inverse kinematics. Expected kinetic energies and emission angles of the different light charged particle ejectiles are shown in figure 1, for c.m. energies between 0 and 5 MeV above neutron emission threshold. The selected kinematical regions correspond to forward c.m. angles where direct transfer reaction cross sections are maximum. The characteristics (E_{cm} and θ_{cm}) of the unknown unbound system produced by the two-body reaction can be deduced from the measured energies and emission angles of the light ejectiles. One notes the focussing of both ^{3}He and ^{6}Li ejectiles in a narrow cone at forward angles, whereas protons from the (d,p) reaction with c.m. angle $\leq 30^o$ are emitted in the whole backward hemisphere. Two separate experiments involving different geometrical arrangement of the charged particle detectors were then performed for the study of ^{9}He and the missing mass measurement of 4n and ^{7}H systems.

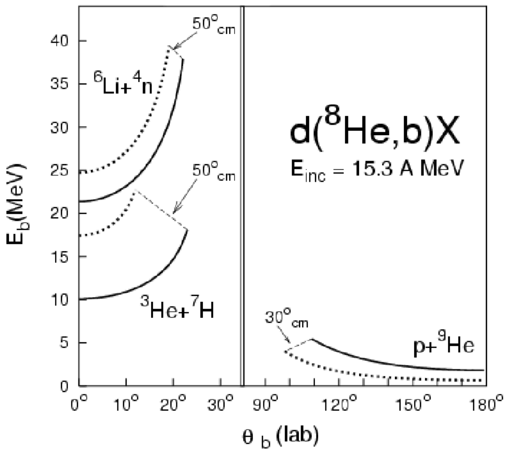
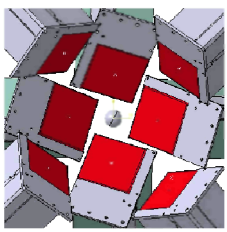


FIGURE 1. Energy-angle relations for light charged-particles "b" produced in ^{8}He+d interaction and unbound nuclei X at c.m. energy E_{cm}=0 MeV(solid lines) and E_{cm}=5 MeV (dotted lines)

The(d,p) experiment

Protons from the d(^{8}He,p)^{9}He reaction emitted at backward angles have quite low kinetic energy ($E_p \leq 5$ MeV). The choice of the CD_2 target thickness (0.8 mg/cm^2) resulted from a compromise between the desired statistics and the global resolution ($\simeq$0.5 MeV) in ^{9}He c.m. energy. Protons were detected between 110 and 170 degrees using the eight MUST Silicon telescopes [2] placed at $\simeq$ 10 cm from the target. They were stopped in the 300 μm thick,60x60 mm^2 position sensitive double-sided Silicon strip detectors (DSSD), which constitute the first stage of the MUST array. The eight DSSD were backed by 58$\times$58 mm^2, 3mm thick Si(Li) detectors, which were used in anticoincidence for background reduction. The geometical arrangement of the eight telescopes is shown in fig.2. Protons produced in the target were identified by time-of-flight measurement.



b)

FIGURE 2. Schematic view of the MUST array in the "(d,p)" geometry.

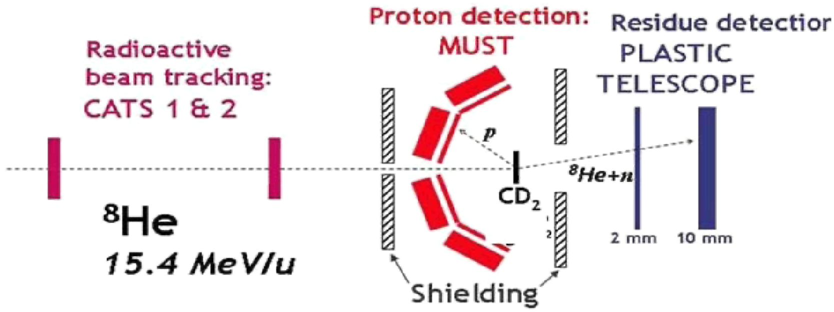


FIGURE 3. Schematic view of the experimental setup, used in the d(^{8}He,p)^{9}He experiment

The beam particles and residues emitted at forward angles were detected in a telescope of two 20×20 cm^2 rectangular plastic scintillators with thickness 2 mm and 10 mm, respectively. A schematic view of the set-up used in the (d,p) experiment is shown in fig.3. Efficient background reduction was insured by gating the events with plastic signals corresponding to Helium ions produced by the decay of ^{9}He.

The (d,^{6}Li) and (d,^{3}He) experiment

A 1.6 mg/cm^2 thick CD_2 target was used in the second experiment investigating the ^{7}H and 4n unbound systems A large amount of beam time was also devoted to measurements using a pure carbon target, in order to evaluate the contribution of C atoms in the target to the 4n and ^{7}H missing mass spectra. The ^{3}He and ^{6}Li ions were detected using only four telescopes of the MUST array, placed at forward laboratory angle ($8^o \leq \theta \leq 23^o$). Additionnal 4x4cm^2,70 μm thick Silicon strip detectors provided by JINR Dubna were placed in front of the MUST telescope for ΔE-E identification of light charged ejectiles. A typical identification spectrum of Helium and Lithium ejectiles is shown in fig.4, the parameter PID being proportional to log(ΔE-E). The ^{6}Li ejectiles were well separated from ^{7}Li and other particles. A ^{3}He peak could also be observed in the tail of the ^{4}He peak.

Four 160x160 mm^2 plastic scintillators with thickness 180 mm were placed behind MUST at 600 mm from the target position in order to detect neutral residual particles. Their geometry was defined in order to ensure optimal detection efficiency for an eventually bound tetraneutron (with binding energy $E_{cm} \simeq 0$) in coincidence with ^{6}Li detected in MUST. Coincidence of MUST events with neutrons detected in the plastic scintillators could be efficiently employed to reduce background in the continuum spectrum of the 4n system. This advantage was however obtained at the cost of some loss of available statistics, compared with singles data. On the other hand, this setup had only small efficiency for the detection of the triton and the four neutrons in coincidence with ^{3}He ejectiles in MUST, as a large fraction of residual particles were emitted in the central hole between the plastic blocks.

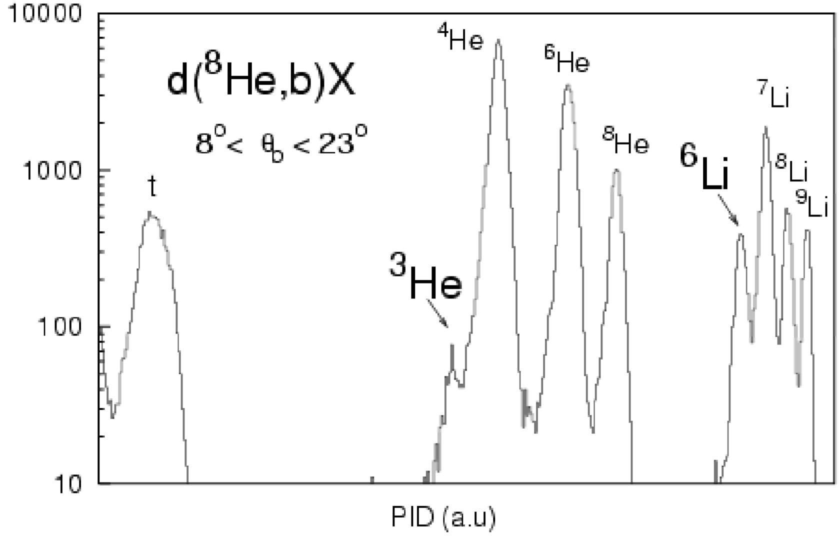


FIGURE 4. Particle Identification using Silicon telescopes at $8^o \leq \theta_{lab} \leq 23^o$

Missing mass determination procedure

The determination of E$_{cm}$ involves the precise measurement of both kinetic energy and emission angle of the charged ejectile, deduced from impact positions of incident beam on target and ejectile in the MUST strip detectors. An accurate angular determination can be obtained due to the 1mm width of both X and Y strips of MUST. Energy calibrations of each of the 960 strips was performed using a mixed ^{233}U-^{239}Pu-^{241}Am α source placed at the target position. The energy resolution was approximately 60 keV (FWHM). Monte-Carlo simulations including all the details of the experimental setup were performed to calculate detection efficiency and expected resolution in E$_{cm}$. Overall checks of the experimental setup and data analysis procedure were obtained in separate runs using either the primary ^{13}C beam or ^{12}C and ^{16}O beams accelerated by CIME. The corresponding spectra of well known stable nuclei produced via the (d,p), (d,^{3}He) and (d,^{6}Li) reactions in inverse kinematics could then be compared with data from the litterature, thus confirming the validity of our analysis.

RESULTS

4n

The existence of bound or quasi-bound ^{4}n system (tetraneutron) is a longstanding problem in nuclear physics. A review of theoretical works and various experimental attempts to observe a bound tetraneutron in the last century is given in the 1992 compilation on A=4 nuclei[5]. The advent of neutron-rich radioactive beams offers new opportunities for such investigation. The 6 events consistent with the existence of an eventually bound tetraneutron, observed in the breakup of ^{14}Be[1] have boosted the interest for the study of the 4n system. Several theoretical papers [6, 7] have stressed the huge impact that a bound tetraneutron would have on our present knowledge of nuclear forces. Preliminary results of our missing mass determination of the 4n system via the (d,^{6}Li) α transfer reaction were reported in ref.[3]. That spectrum did not show evidence of the existence of a bound ^{4}n, but suggested the existence of a low-energy resonance in the 4n continuum, located at about 2 MeV above neutron threshold.

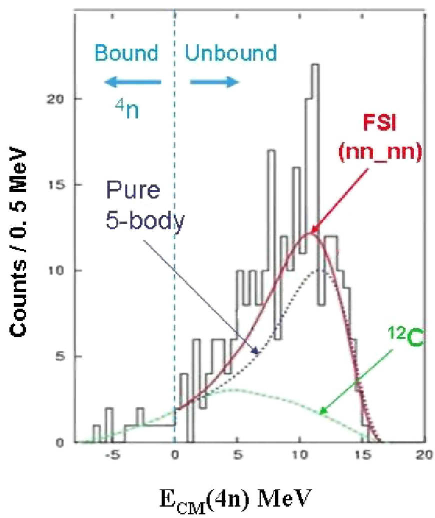


FIGURE 5. Missing mass spectrum of the 4n system produced by the reaction ^{8}He(d,^{6}Li) in inverse kinematics. Here the ^{6}Li ejectiles are gated by neutron(s) detected in the plastics scintillators.

The present results were obtained with increased statistics and a better estimation of the background due to carbon contaminant. A detailed description of the experiment and subsequent analysis is given in ref.[8].The missing mass spectrum of the 4n system gated by neutrons in the plastics scintillators is shown in fig.5. The dashed line is the estimated background due to carbon in the CD_2 target. The 5-body phase-space spectrum (dotted line) in fig.5 was normalized to the data at high energy and added to the Carbon background.

As in our previous work, one does not observe any peak in the negative energy region which would correspond to the existence of bound tetraneutron. The existence of a narrow low-lying structure suggested in ref.[3] is not confirmed by the present data. However the spectrum of fig.5 cannot be reproduced by pure 5-body phase space calculations. The excess of counts over the phase-space below 10 MeV strongly suggests the existence of correlations between the 4 neutrons emitted in the d(^{8}He,^{6}Li) reaction. Introduction of final state interactions (FSI) nn-nn in the calculated spectrum (full line) improves the agreement with the data. Similar analyses will soon be performed in the 2n and 3n systems emitted in the d(^{8}He,^{8}Li) and d(^{8}He,^{7}Li) reactions also observed in the present experiment (cf. fig.4).

^{7}H

Experimental information on the very exotic ^{7}H nucleus can be provided by missing mass measurements using a secondary beam of ^{8}He. The first evidence of a low-lying resonance in the p+6n system was obtained at Riken[9] using the p(^{8}He,2p)^{7}H reaction at 61 A MeV. They observed a structure just above the t+4n threshold superimposed over a large background. However the poor c.m. energy resolution and the large statistical error bars did not allow to extract accurate information on its energy and width.

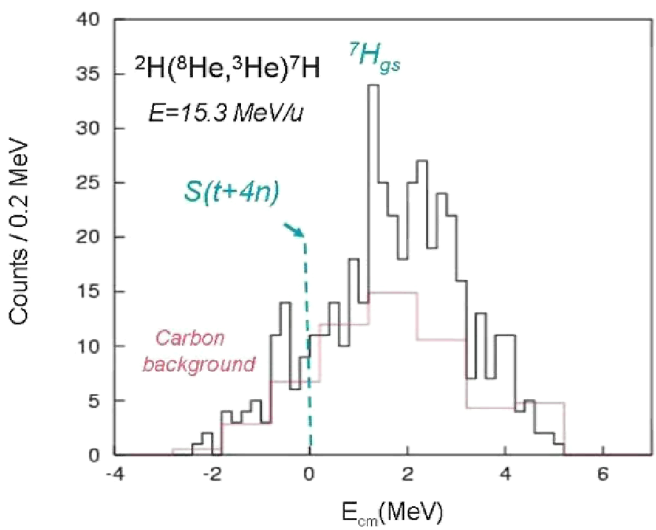


FIGURE 6. Missing mass spectrum of ^{7}H produced by the reaction ^{8}He(d,^{3}He) in inverse kinematics..

The present proton transfer experiment d(^{8}He,^{3}He)^{7}H is well adapted to the search for a low-energy resonance in the ^{7}H system, due to the large c.m. solid angle covered by the MUST detector (cf. fig.1). However production cross sections at 15.3 A MeV incident energy predicted by DWBA calculations (using code Dwuck4[10]) are quite low ($\simeq$ 30μb/sr), corresponding to only a few tens of counts in the whole resonance.

The identification spectrum in fig.4 shows evidence for the presence of ^{3}He ejectiles, which remains after subtraction of carbon background. Identification contours in the bidimensional spectra E-PID were carefully defined using data from the auxilliary study of the d(^{12}C,^{3}He) reaction, in order to minimize the background from other sources. Figure 6 displays the experimental c.m. energy spectrum measured in the ^{8}He+CD$_2$ experiment, together with the background due to reaction on carbon atoms in the target (which was deduced from the run with the C target). The missing mass spectrum of the t+4n system obtained by subtracting this background cannot be reproduced by the calculated 6-body phase-space (convoluted with the energy acceptance of the setup) which is maximum at $\simeq$ 4 MeV above the t+4n threshold. On the other hand, this spectrum clearly exhibits a resonant structure which centroid is located at about 2 MeV, in agreement with the results of ref.[9]. This low-lying resonance in the t+4n system can be identified with the ground state of ^{7}H.

^{9}He

A summary of existing experimental results about ^{9}He and related theoretical works can be found in the 2004 compilation of Tilley et al.[11]. Information on ^{9}He was mainly obtained using double-charge exchange reactions on a ^{9}Be target. A resonance observed both in (π^-,π^+) [12] and (^{14}C,^{14}O)[13] at $\simeq$1.2 MeV above the n+^{8}He threshold was considered as the ^{9}He ground state, with dominant $p^4_{3/2}p_{1/2}$ configuration. On the other hand,a recent analysis of a two-proton knock-out reaction on ^{11}Be[14] has concluded to the existence of an unbound s state with energy less than 0.2 MeV above threshold, corresponding to the "true" ^{9}He ground state with J^π=1/2$^+$. Additionnal information on this very exotic nucleus with extreme N/Z ratio was therefore needed. The present study of the unbound nucleus ^{9}He was performed via the (d,p) reaction, which is the standard tool for the determination of neutron single-particle distributions.

Figure 7a displays the energy spectrum of ^{9}He, obtained for protons with kinetic energy 0.8$\leq E_p \leq$ 5 MeV, and gated by plastic events. One notes the quasi-absence of counts in the negative part of the spectrum, due to the coincidence with Helium ejectiles. Two narrow states are observed at 1.3 and 2.3 MeV above neutron theshold, in good agreement with results of double-charge-exchange experiments [12, 13]. The dotted line in fig.7a shows the 3-body phase space convoluted with the setup acceptance and energy resolution, and arbitrarily normalized to the data. The striking feature is the presence of counts around neutron emission threshold. This structure can be identified with the ^{9}He ground state, proposed by ref.[14] at E_{res} <0.2 MeV. The observed angular distribution, which is forward-peaked in the c.m. system, in fact excludes that its origin could be due to phase space effects.

Figure 7b displays the angular distributions of the ground state and the first excited state (previouly considered as ^{9}He ground state). They are compared with the predictions of standard DWBA calculations for various values of the transferred angular momentum L. The ground state angular distribution is well reproduced by L=0 calculations. The ground state of ^{9}He may then be considered as a new example of a "virtual" s state discussed in textbooks, like the one previously seen in the neighbouring nucleus ^{10}Li[11].

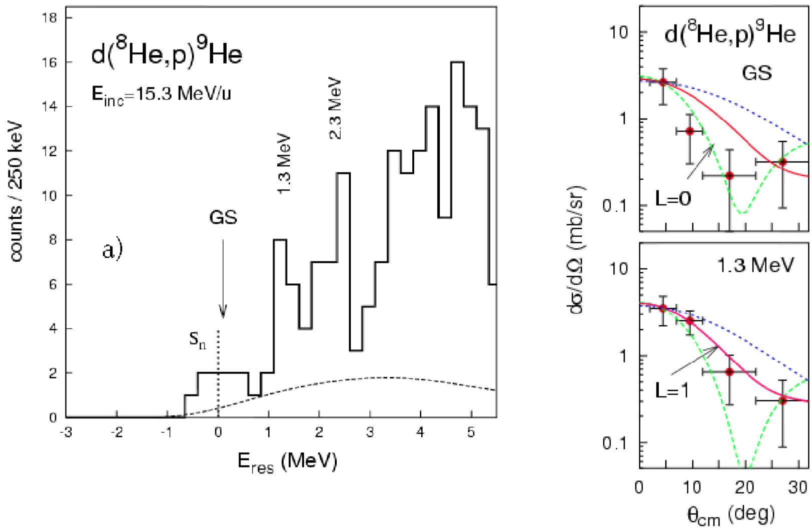


FIGURE 7. *a)* Missing mass spectrum of ^{9}He; *b)* Angular distributions compared with DWBA predictions. The calculated L=0,1 and 2 angular distributions are shown as full, dashed and dotted line, respectively.

A L=1 angular distribution is observed for the first excited state of ^{9}He, which may be identified with the $1/2^-$ state predicted by most theoretical calculations[11] to be ^{9}He$_{GS}$. However this resonant state represents only the low-lying fragment of the $p_{1/2}$ single-particle strength in ^{9}He, as attested by both the narrow width of this resonance[11] and the $p_{1/2}$ spectroscopic factor of 0.14 deduced from the present DWBA analysis.

The L=0 and L=1 angular distributions respectively measured for the ground state and the first excited state of the unstable nucleus ^{9}He clearly demonstrate the existence of shell inversion between the $s_{1/2}$ and $p_{1/2}$ neutron orbitals, as previously observed[11] in the heavier N=7 neutron-rich nuclei ^{10}Li and ^{11}Be.

CONCLUSION

Very exotic nuclear systems were studied via transfer reactions using the ^{8}He secondary beam of SPIRAL and the Silicon strip detector array MUST. Important information about unbound nuclei with extreme neutron-proton asymmetry (^{9}He and ^{7}H) and pure neutronic matter (the tetraneutron ^{4}n) were obtained:

a) Identification of ^{9}He$_{GS}$: $s_{1/2}$ state at threshold;

- Evidence for $s_{1/2}$-$p_{1/2}$ shell inversion in ^{9}He

b) Observation of a resonance in the ^{7}H missing mass spectrum;

c) Existence of correlations in the 4n system.

Investigations of exotic nuclei close to and beyond the stability line will soon be pursued at Ganil using the new generation of Silicon Strip detector MUST2, which will be operational at the end of 2006.

ACKNOWLEDGEMENTS

P.Gangnant and J.F.Libin are warmly acknowledged for their assistance during this experiment. One of the authors (R.W.) wishes to thank the IN2P3-Pologne agreement for financial support. The work of K.W.K was supported by the U.S. National Science Foundation.

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