Unbound states studied by direct reactions

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Abstract. The t(6He,8He)p t(8He,10He)p reactions were studied in experiments with 25A MeV 6He beam and 27.4A MeV 8He beams and an unique tritium gas target. Results on the 8He and 10He excitation energy spectra are presented. The 8He spectrum exhibits 3 states, apart of the ground state and known (2+) state at 3.6 MeV, the third state is seen at 5.4 MeV. A tentative assignment 1+ is proposed for this structure. The 10He spectrum shows no event at the excitation energy below 3 MeV what is in contradiction with the earlier reports on this nucleus. A high statistics of α-n coincidence events collected for the 8He beam run has been subjected to analysis in order search for the bound tetraneutron. The search produced a negative result.

1. Introduction

The properties of radioactive nuclei far from stability line are extensively studied. New phenomena have been found which are not present for nuclei close to the stability line. It is interesting to investigate the evolution of nuclear structure along the isotopic chains towards the drip line and beyond. The unbound states of the light neutron-rich systems are a challenging subject for both theory and experiment. The ab initio calculations [1] well reproduce the binding energies of the light nuclei (A<10) but are less successful in the description of unbound excited states. Reliable experimental results are rather scarce for the spectroscopy of extremely neutron-rich nuclei. Direct reactions with exotic beams offer effective method to do the spectroscopy study of nuclear system having the large excess of neutrons. An advantage of this approach is the simple reaction mechanism. Its relative transparency offers more predictive power than other reactions like the massive transfer or the multi-nucleon exchange, for example. It has been recently demonstrated that the 2-neutron transfer reaction t(t,p)5H investigated at a condition of complete kinematics is quite productive for the extraction of spectroscopic information on the particle unbound states [2]. The method has been later applied to the study of the 9He nucleus performed with the (d,p) reaction on a 8He beam [3]. The experimental approach combines the measurement of the proton production yield at scattering angles, close to the beam axis in CM, and the angular correlations obtained between the protons and charged products from the 9He decay. The close to “zero angle” geometry for the transfer process ensures that only zero projection of angular momentum on the quantization axis is populated thus the highest spin alignment is achieved in the final state. Therefore, the angular correlations for the particle decays from the
aligned states are quite distinguishable for different spins-parities and possible admixture of different spin states. In the case of the $d(\text{He}^9, \text{He})p$ reaction, the spin-parity sequence of low laying energy states has been established in an unambiguous way by the analysis of angular correlations [3]. We have demonstrated the possible existence of a virtual $S_{1/2}$ state in the $\text{He}^9$ spectrum [3]. A lower limit of $a > -20 \text{ fm}$ has been proposed for the scattering length characterising this structure. It means that the much discussed S-state inversion phenomenon for $N=7$ isotones has been observed in $\text{He}^9$ as well. The contribution of the $S_{1/2}$ strength in $\text{He}^9$ has implications for the $\text{He}^{10}$ structure. The existence of a narrow near-threshold $0^+$ state in $\text{He}^{10}$, having $[s_{1/2}]^2$ structure, in addition to $[p_{1/2}]^2$, has been suggested in a paper [4]. More on the theoretical interpretation of $\text{He}^{10}$ spectrum in context of the $\text{He}^9$ data can be found in Ref. [5]. This situation and the scarcity of the experimental data on the $\text{He}^{10}$ system prompted us to investigate the $t(\text{He}^6,\text{He})p$ reaction. A similar reaction of almost the same kinematics but with the $\text{He}^9$ beam i.e. the $t(\text{He}^6,\text{He})p$ one has been studied as well as a reference. There has been a spectacular announcement on a possible observation of a bound 4-\text{n} system in the fragmentation of $\text{Be}^{14}$ beam nuclei [6]. If confirmed, this finding could be of fundamental importance.

A body of $\alpha$-\text{n} coincident events from the $\text{He}^8$ beam interactions with the target gas cell has been subjected to the same analysis as in Ref. [6] in a search for the bound 4-\text{n}, see chapter 3.

2. Spectroscopy of $\text{He}^{10}$ and $\text{He}^9$ by ($t,p$) reaction

2.1. Experimental conditions

Primary beam of 34 MeV/n $\text{B}^{11}$ nuclei was provided by the $U-400M$ cyclotron of FLNR. Secondary beams of $\text{He}^9$ and $\text{He}^8$ nuclei were produced by the $\text{B}^{11}$ fragmentation on a $\text{Be}$ production target. Fragments of interest were separated from other reaction products in the separator ACCULINNA [7] and focused on a unique tritium gas target [8]. A beam spot was a circle of 20 mm of diameter. The target cell of 4mm length was sealed by double entrance and exit stainless steel windows, each window of 12.7 µm thick. The cell was cooled down to 28K and contained $2 \cdot 10^{20}$ cm$^{-2}$ tritium atoms at a pressure of 900 mPa. The intensities of $\text{He}^6$ and $\text{He}^8$ projectiles on the target were around of $10^4$ s$^{-1}$ and $6 \cdot 10^3$ s$^{-1}$, respectively. The beam contaminations, monitored on-line by the beam diagnostics, were below a level of 10%. The diagnostic, placed upstream the target on a 8 m base, was dedicated for measuring the time of flight of the beam nuclei, their energy loss in a thin detector and the beam tracking accomplished by the two position sensitive multi-wire chambers separated by a distance of 54 cm. In that way the energy of each projectile, its identification, the impact position on the target (1.25 mm resolution) and projectile inclination angle with respect to the geometric axis were provided. The mean energies of $\text{He}^9$ and $\text{He}^8$ beams in the middle of the target were 25.0 MeV/n and 27.4 MeV/n, respectively. The energy spread was 8.5% and angular divergence 0.23 deg. (FWHM). In order to reduce the influence of the beam halo an active collimator (veto) was placed just upstream the target.

Figure 1. Experimental setup and kinematical scheme.
Experimental setup and a scheme of reaction kinematics are shown in figure 1. Protons from \((t,p)\) reactions, emitted backward, were detected by a telescope consisting of 300 µm and 1 mm annular Si detectors. Their active areas had the outer and inner diameters of 82 mm and 32 mm respectively. The telescope was installed 10 cm upstream the target and covered an angular range of 9-21 degrees in the lab system. The first, thin detector was segmented in 16 rings on one side and 16 sectors on the other side. The second, thick detector was not segmented. Position sensitive, forward angle telescope for the \(^8\text{He}\) and \(^6\text{He}\) detection was installed on the beam axis at a distance of 28.8 cm in the run with the \(^6\text{He}\) beam and 36.5 cm in the case of the \(^8\text{He}\) beam. The telescope was composed of 6 squared (60 x 60 mm) 1 mm thick detectors. The first two detectors of the telescope were segmented in 16 strips in horizontal and 16 strips in vertical directions. The resolution of this telescope in energy and position allowed us to know the emission angles and energies of charged decay products (\(^6\text{He}\) and \(^8\text{He}\)) obtained in the CM system of the parent nuclei \(^8\text{He}\) and \(^6\text{He}\).

An array of 48 modules of DEMON neutron detecting system was installed at a distance of 3.1 m from the target. The triple \(p-\text{6He}-n\) coincidences could demonstrate the cases of the complete 4-body kinematics. One may find more details on the experimental setup in the forthcoming paper [9].

Evens of the 2-neutron transfer reactions were identified as coincidences between protons registered in the backward telescope and \(^8\text{He}\) or \(^6\text{He}\) particles in the forward telescope. The inclusive spectrum of charged particles in the back telescope was mostly generated by the reactions in the stainless steel windows of the gas target cell. Therefore \(p-\text{He}\) or \(p-\text{He}\) coincidences were instrumental to obtain excitation spectra of interest. Monte Carlo simulations which took into account all experimental conditions resulted in a value of 450 keV for the expected excitation energy resolution for the both \(^8\text{He}\) and \(^4\text{He}\) systems. The uncertainty of the beams energy measurement contributed most to this value.

2.2. Experimental results

The excitation spectrum of \(^8\text{He}\), obtained from the spectrum of protons detected in coincidence with the signals of either \(^6\text{He}\) or \(^8\text{He}\) coming from the backward, is shown in figure 2, the upper panel (a).

![Figure 2](image)

The shadowed histogram in panel (a) indicates the ground state. The energy resolution for this peak is somewhat deteriorated due to a high background in the thick detector caused by the beam halo irradiating the back side of the detector. This effect is reduced in the case of lower energy protons which were completely stopped in the thin (300 µm) detector because of its high segmentation. The second peak was assigned to the \(2^+\) state at 3.6 MeV. This agrees with the results of other experiments, see [10] and references therein. It is proposed that the next peak is a \(1^+\) resonance at 5.4 MeV. This assumption is based on various theoretical predictions concerning the third state of \(^8\text{He}\) \([1,11-12]\).
$^8$He spectrum obtained from the triple coincidence ($p$-$^6$He-$n$) events is shown in the lower panel (b) of figure 2. The cross-section for populating $^8$He ground state averaged over 4°-10° CM angular range was estimated to be ~200 µb/sr. This quantity for $^8$He ($2^+$) state in the same angular bin is ~250 µb/sr, if no other structure is present in vicinity of that peak. These cross-section values could be used to extract information on the $^8$He ground state wave function.

Figure 3 presents DWBA (code FRESCO [13]) calculations for the population of the two $^8$He states in the 2-neutron transfer reaction $t(^6$He,$^8$He,$p$) at 25 MeV/n for the $^6$He beam energy. The processes were treated as 1-step ones. The calculations for the $2^+$ state were done for two options. The dotted line in figure 3 corresponds to a weakly bound $2^+$ state with the binding energy of 0.04 MeV, whereas the dashed one is for a resonant state at the resonance energy of 1.7 MeV.

Figure 3. The two-body DWBA predictions of the differential cross-section for the one-step 2-neutron transfer reaction $t(^6$He,$^8$He,$p$) leading to the ground and ($2^+$) excited states at the beam energy of 25 MeV/n. The solid line is for the ground state. The dashed line is for the excited unbound state at 3.6 MeV of excitation energy in respect to the ground state. The dotted line is for the ($2^+$) state taken as a weakly bound one. All spectroscopic factors are set equal to 1.0.

The relevant Optical Model (OM) parameters for the entrance and exit channels were taken from literature. Since the lack of the triton elastic scattering data for nuclei in question, the needed OM parameters were borrowed from the study of 45 MeV $^3$He elastic scattering on stable p shell nuclei [14]. A family of the OM parameters for $^6$Li+$^3$He system was used for the entrance channel. The exit channel OM parameters were derived by means of the “global” phenomenological CH89 algorithm [15]. The same approach was used in order to obtain parameters for the core-core interaction, i.e. $p$-$^6$He, needed for a remnant term in the transition amplitude. The inclusion of the remnant term provides a convergence of the post-prior representations of DWBA. It is known that the absolute value of DWBA cross-section is questionable due to inherent approximations applied. However, the ratio of the cross-sections obtained for two states in the same reaction is more physically meaningful. All spectroscopic factors are equal to 1.0 for the calculations shown in figure 3. Therefore these results demonstrate dynamical effects of the 2-neutron transfer strengths for the transferred orbital angular momentum $L = 0$, and 2. The difference for the bound and unbound treatments of $^8$He ($2^+$) wave function, see dotted and dashed curves in figure 3 respectively, may be attributed to a difference in the rms radii for these options. One could see in figure 3, that the transition probability to the excited state is 4-5 times higher than for the ground state. Since the experimental data, averaged in the angular bin of 4-9 deg. CM, are comparable, see figure 2, it implies that the spectroscopic factor for the $^6$He -2n clustering in the $^8$He ground state is 4-5 times higher than in the $2^+$ one. A more quantitative analysis requires taking into account possible contributions from various 2-step processes to the population of the $^8$He states. The most important 2-step process seems to be the sequential 2-neutron transfer through the intermediate resonant $^7$He ground state. It has been found in the studies of the reverse reaction $p(^8$He,$^6$He)$_t$ that the 2-step transfer through the $^7$He ground state contributes quite significantly [16-17]. One can hope that for the reactions of interest this effect can be less important because of the higher CM energy. It is desirable to collect more statistics for the $^8$He spectrum what could be achieved in a forthcoming experiment at this Laboratory.

Results on the $^{10}$He system are shown in figure 3. Panel (b) shows the excitation spectrum for $^{10}$He obtained from $p$-$^8$He coincident events. Panel (a) shows the 2-dim distribution of the $^8$He energy (in $^{10}$He CM system) for the $^8$He + 2n decays of $^{10}$He. It can be seen that for the events grouped in the
region of the $^{10}$He lowest energy peak the $^8$He decay energy is close to the kinematical limit which is equal to 1/5 of the $^{10}$He excitation energy. It means that for this $^{10}$He state the decay is almost of two-body kinematics. This implies a rather low momentum in the system of 2-neutrons for this state.

![Figure 4. Excitation spectrum for $^{10}$He obtained from $p-8$He coincident events, panel (b). Two dimension plot of $^8$He energy in CM of $^{10}$He vs its excitation energy, panel (a). The dashed line in panel (a) is the kinematical limit for this $^8$He energy equal 1/5 of the $^{10}$He excitation energy. The shadowed area in panel (a) represents physically allowed region with the resolution taking into account. The dotted line in panel (b) is for the experimental efficiency. It can be seen in panel (a) that events corresponding to $^{10}$He ground state are grouped close to the $^{8}$He kinematical limit.](image)

Cross-section for the production of events seen at 3 MeV of excitation, averaged over the angular distribution region of 3.5°-9.5° CM, was estimated to be ~ 140 µb/sr. The absence in figure 4 events below 2.5 MeV of the $^{10}$He excitation is in disagreement with the interpretations of earlier data obtained in other reactions [18-19]. Lower energies have been concluded for the $^{10}$He ground state there. The relatively high energy for the $^{10}$He ground state could set a new upper limit for the s wave strength in the $^5$He nuclei [4-5].

### 3. A search for the tetraneutron

The existence of 4-neutron system as a bound particle is a long standing problem for theory and experiment, e.g. see compilation on $A=4$ systems [20]. Numerous attempts to obtain such particle i.e tetraneutron have been undertaken: in uranium fission by fast and thermal neutrons, in heavy ions reactions, in spallation, by pion photoproduction on $^4$He, the capture of negative pions by $^7$Li. In spite of all efforts no convincing evidence for bound or even resonant 4-n system has been found, [20] and references therein. Therefore the report on a possible observation of a bound tetraneutron [6] has been met with the great interest. In an experiment at GANIL a $^{14}$Be beam has been fragmented on a target. Neutrons in coincidence with $^{12}$Be and $^{10}$Be products have been measured by an array of DEMON neutron detectors. The DEMON modules give signals of the neutron time-of-flight (ToF) and the energies of protons recoiled in the detector. For a neutron registered in the detector the recoiled proton energy must not exceed the neutron energy measured by ToF. The authors of Ref. [6] have shown that 6 events in their recoiled proton energy spectrum were well beyond the energy limit for common neutrons. It is notable that these interesting events were in coincidence with $^{10}$Be, but not with $^{12}$Be. Because of that finding a suggestion has been issued on the existence of the bound $^7n$ (tetraneutron). Theory considers such finding as irreconcilable with the present knowledge of the nuclear interactions, see for example [21]. The availability of the $^8$He beam, neutron (DEMON) and charge particle detectors in our experiment offers an opportunity to check whether a similar effect could be seen in the collected data. The $^8$He nucleus could be considered as a system composed of a well defined $^3$He particle core and 4 neutrons. Within the translation invariant shell model (TISM) the a-4n clustering in $^8$He has been found to be large [22]. The 4-n cluster is treated there as a fully antisymmetrized object having 2-neutrons in s shell and 2-neutrons in p one.

The a-neutron coincidence data obtained from interactions of the $^8$He beam with the gaseous target have been analyzed in a way of Ref. [6] ($^{14}$Be experiment). The recoiled proton energy spectrum
measured by DEMON detectors is shown in figure 5. An inspection of figure 5 leads to a conclusion that the spectrum is free of events attributable to the bound $^4n$ system.

Figure 5. The recoiling proton energy spectrum obtained from DEMON detectors at a condition of $\alpha$–neutron coincidences. The 26.5 MeV/n $^8$He beam bombarded the tritium gas enclosed within stainless steel windows. The proton energy shown in abscissa is a ratio of the proton energy to the neutron energy measured by the time of flight method. The physical limit for the proton energy is equal to 1.0 in these units. Deviation from rectangular shape is caused by finite resolutions of the proton and neutron energy measurements. It can be seen that there is no event exceeding the recoiling energy limit for the common neutron.

4. References

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Acknowledgments
The authors wish to acknowledge the financial support from the INTAS Grant No 05-1000008-8272, Russian RFBR Grants No. 05-02-16404 and No. 05-02-17535 and Russian Ministry of Industry and Science grant NS-1885.2003.2