New measurements of the mass of isotope ^{4}H in reactions with a radioactive ^{6}He beam and ^{6}Li ions

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(Submitted 18 May 1995)
Pis'ma Zh. Éksp. Teor. Fiz. **62**, No. 1, 18–22 (10 July 1995)

The cross sections of the reaction D(^{6}He, α) at $E_{^6\mathrm{He}} = 19.3$ MeV were measured for the first time. Two resonances were observed in the α particle spectrum. The resonances correspond to the ground and excited states of the nuclear-unstable isotope ^{4}H that lie 2.0±0.3 MeV and 5.2±0.5 MeV above the $^4\mathrm{H} \rightarrow t+n$ dissociation threshold. It is assumed that the excited state of ^{4}H has the configuration $(d+\ ^2n)$ and the quantum characteristics 1^+. The nuclear instability of ^{4}H (2.3±0.3 MeV) is confirmed by measurements of the reaction ^{6}Li(^{6}Li,^{8}B) at the energies $E_{^6\mathrm{Li}} = 85$ and 93 MeV. As a result, a new value is obtained for the ^{4}H mass defect: 25.3±0.3 MeV. © *1995 American Institute of Physics.*

The existence of the nuclear-unstable isotope ^{4}H, which is the lightest neutron-excess nucleus that is unstable with respect to decay into $t+n$, was discovered more than a quarter of a century ago. Nonetheless, degree of its instability has still not been unequivocally determined. In Ref. 1 it is shown that ^{4}H is underbound by 2.3–2.6 MeV, while in later works[2-7] it is asserted that the decay $^4\mathrm{H} \rightarrow t+n$ is accompanied by the release of 3.1–3.8 MeV of energy. There is now a general acceptance of the data obtained from phase analysis of the elastic neutron scattering by tritium,[8] which explain the polarization and interaction cross section of $n+T$ by the presence of wide p–single–particle resonances lying 3.4 MeV (2^-) and 5. 1 MeV (1^-) above the $^4\mathrm{H} \rightarrow t+n$ dissociation threshold. However, in Ref. 9 it was shown, after a careful investigation of the excitation function of $n+T$ and $p+\ ^3$He, that the existing experimental data do not permit making a choice between several sets of phases and for this reason the results of the analysis performed in Ref. 8 are ambiguous. One would think that the single-particle states in the system ^{4}H should be effectively manifested in the simple stripping reaction T(d,p). This reaction was studied in Ref. 1, where a wide resonance was observed 2.3–2.6 MeV above the $t+n$ decay threshold, but it was noted that the energy of this peak depends on the angle of detection of the protons. The reason that the ^{4}H mass cannot be determined reliably in the reaction T(d,p) is probably that the energy of the decay $^4\mathrm{H} \rightarrow t+n$ (~2.4 MeV) is close to the binding energy of the deuteron (2.22 MeV). For this reason, the protons from the decay of the deuteron in the process T(d,np)T can distort the spectrum of the reaction T(d,p)^{4}H.

The parameters of the resonance of the system ^{4}H near $\sim$3.4 MeV have been determined in reactions with heavy ions, for example ^{6}Li(^{6}Li,^{8}B) (Ref. 3), ^{9}Be(^{11}B,^{16}O) (Ref. 6), and absorption of π mesons by ^{7}Li and ^{9}Be nuclei.[7] This scatter ($\geqslant$1 MeV) in the decay energy $\varepsilon(^{4}\mathrm{H})$ could be due to the presence of several wide overlapping resonances ($2^{-},1^{-},0^{-}$) in the system[10] $n+t$, which are occupied with different probabilities in different reactions.

Our study was motivated by the uncertainty in the energies and widths obtained in different studies for the resonances of the system ^{4}H. We have studied the system ^{4}H using the reactions D(^{6}He, α) and ^{6}Li(^{6}Li,^{8}B). These reactions have a number of advantages: 1) the transfer mechanism is direct; 2) the background in the experimental interval of the energy spectra of ^{4}He and ^{8}B is low; and, 3) the cross sections at small detection angles is large. The reaction D(^{6}He, α) was investigated first. A radioactive ^{6}He beam with an intensity of $2\cdot 10^{3}$ particles per second with an energy of 19.3 MeV and a resolution of 0.9 MeV was obtained from the reaction ^{14}C(^{7}Li,^{6}He) in a MASÉ magnetic separator.[11,12] The energy spectra of the α-particles were measured at an angle of 6.3° with a telescope of $\Delta E_1-\Delta E_2-E$ semiconductor detectors arranged in a ring. The targets consisted of deuterated polyethylene films with a thickness of 6.5 mg/cm^{2} (deuterium enrichment of up to 98%) and carbon films with a thickness of 7.3 mg/cm^{2}.

Figure 1a shows the α-particle spectrum from the (^{6}He, α) reaction on a CD$_2$ target. Two distinct resonances, which are not observed in the reaction ^{12}C(^{6}He, α), are observed in the spectrum at 22 and 18 MeV [Fig. 1b]. The spectra were calibrated according to the peak due to elastic scattering of ^{6}He ions by the ^{12}C target and the ground state of tritium from the reaction H(^{6}He, α) on a 6.5 mg/cm^{2} thick CH$_2$ target. It should be noted that the content of the light hydrogen isotope in the CD$_2$ target is lower than its content as an impurity in the carbon target. The method for fabricating the carbon target — thermal decomposition of methane — allows for a hydrogen content of 5–10% in the carbon film. Comparing the α-particle spectra in Figs. 1a and 1b shows that the resonances observed in the reaction (^{6}He, α) on the CD$_2$ target cannot be associated with reactions on carbon and on the hydrogen impurity. The strong increase in the number of events on the left-hand side of the spectrum near 15 MeV in Figs. 1a and 1b is due to the fact that not all of the charge from the elastically scattered ^{6}He nuclei is collected in the detector E ("penetration" from the intense peak of elastic scattering at small angles).

Resonance-like structures which are associated with different two-step processes can appear in the spectra of the products of the reactions on the light nuclei (see, for example, Ref. 13). In the case of the interaction ^{6}He + D the following channels are possible in the two-stage reactions whose final products include α-particles:

1) $^{6}\mathrm{He}+\mathrm{D}\rightarrow \mathrm{T}+{}^{5}\mathrm{He}\rightarrow \alpha+n$,

2) $^{6}\mathrm{He}+\mathrm{D}\rightarrow \mathrm{D}+{}^{6}\mathrm{He}^{*}(1.8\ \mathrm{MeV})\rightarrow \alpha+2n$,

3) $^{6}\mathrm{He}+\mathrm{D}\rightarrow 2n+{}^{6}\mathrm{Li}^{*}(2.18\ \mathrm{MeV})\rightarrow \alpha+d$.

Monte Carlo analysis of these processes made it possible to exclude all of the above-listed channels, because the energies and widths of the computed peaks did not agree with the observed values.

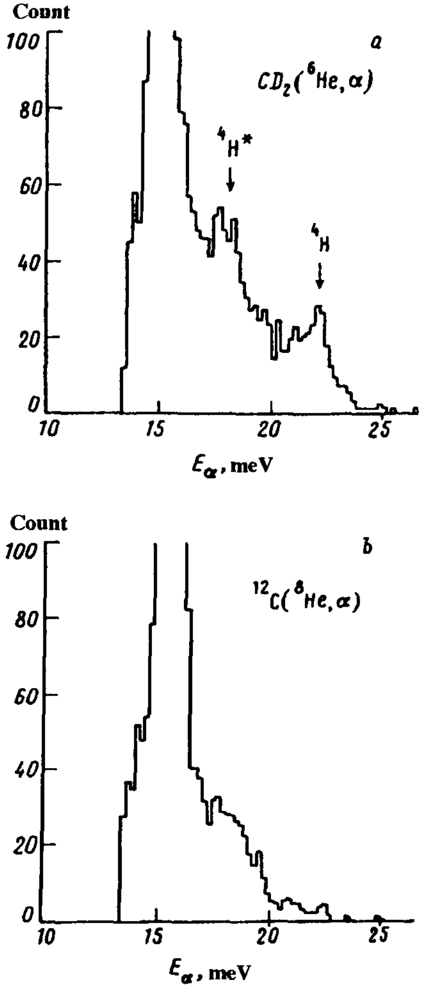

FIG. 1. Energy spectrum of α particles from the reaction (^{6}He, α). The spectrum was measured at an angle of 6.3° on the targets CD_2 (a) and ^{12}C (b).

We thus interpreted the resonances at 22 and 18 MeV observed in the reaction D(^{6}He, α) as an unbound ground state and an excited state of ^{4}H. Their decay energies ε are 2.0±0.3 MeV and 5.2±0.5 MeV, respectively. We note that the excited state lies near the threshold of the decay $^4\mathrm{H} \rightarrow d+2n$ (6.2 MeV). The large cross section for the filling of this state ($d\sigma/d\Omega=38\pm 10$ mb/sr in the center-of-mass system), the high probability for transferring a deuteron as a cluster in the reaction (^{6}He, α),[12] and the relatively narrow width of its decay ($\Gamma=1.2\pm0.4$ MeV) suggest that the resonance with $\varepsilon=5.2$ MeV in ^{4}H corresponds to the configuration $(d+{}^2n)$. The structure of this state can be described in the shell model as $(1s)^2$ $(1p)^2$ and the decay into $t+n$ with the release of energy $\varepsilon=5.2$ MeV is possible when one neutron emerges from the $1p$ shell and at the

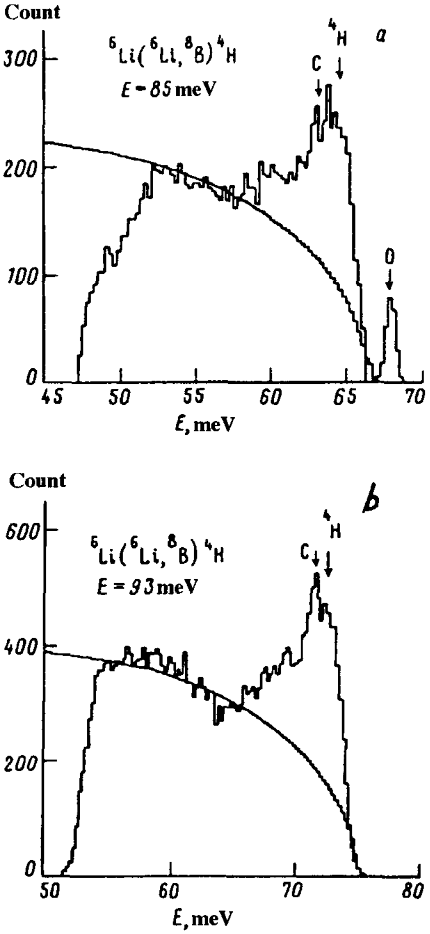

FIG. 2. Energy spectra of the reaction ^{6}Li (^{6}Li,^{8}B)^{4}H. The spectra were measured at the energies $E_{^6\mathrm{Li}}$ = 85 MeV (a) and $E_{^6\mathrm{Li}}$ = 93 MeV (b). The solid lines represent the computed curves of the three-particle phase volume of $^8\mathrm{B}+t+n$.

same time the other neutron makes a transition from the $1p$ shell into the $1s$ shell, thereby forming the stable ^{3}H configuration. The rate of this decay process must be lower because of the small phase volume of this double transition. On the basis of the hypothesis that the transfer of a deuteron with spin and parity 0^+ predominates in the reaction (^{6}He, α),[12] the spin and parity 1^+ can be assigned to the state of ^{4}H with decay energy 5.2 MeV.

Our investigations of the reaction (^{6}He, α) established that ^{4}H is underbound by 2.0 ± 0.3 MeV. This agrees with the investigation of the reaction T(d,p)[1] and disagrees sharply with the experimental data of Refs. 5–9 and the value $\varepsilon = 3.5$ MeV obtained in the reaction ^{6}Li(^{6}Li,^{8}B).[3] To eliminate this discrepancy, measurements of the ^{4}H mass were performed in the reaction ^{6}Li(^{6}Li,^{8}B). The reaction (^{6}Li,^{8}B) was studied for two energies of the incident ^{6}Li ions (85 and 93 MeV). A 0.25-mg/cm^2-thick target of enriched ^{6}Li (95%) was prepared by depositing on a thin ~0.02 mg/cm^2 zapon film in a special vacuum drawer. The energy spectra of the ^{8}B ions were measured on a MASÉ spectrometer at an angle of 2° in the laboratory system. The measurements performed at small angles with solid angle of 10^{-3} sr made it possible to improve by several factors the statistical accuracy obtained in Ref. 3 .

An intense peak, corresponding to filling of the ground state of the ^{4}H nucleus, is seen in the energy spectrum measured at $E_{^6\mathrm{Li}} = 85$ MeV [see Fig. 2a] in the hard part of the spectrum. For calibration purposes and to determine the impurities in the ^{7}Li target, control measurements were performed of the spectra of the reaction (^{6}Li,^{8}B) on a 0.3 mg/cm^2-thick-^{12}C target and a 0.7-mg/cm^2-thick SiO_2 target. Calibration of the spectra according to the known levels of the residual ^{10}Be and ^{14}C nuclei made it possible to determine the decay energy of the ^{4}H nucleus ($\varepsilon = 2.3 \pm 0.3$ MeV) and to identify uniquely the impurity peaks from carbon and oxygen in the ^{7}Li target; these peaks are marked in Fig. 2a by arrows labeled by the letters C and O. As one can see from the figure, the carbon and oxygen impurities do not mask the peak corresponding to the ground state of the ^{4}H nucleus and they make it possible to determine the energy of this peak reliably.

The value obtained for the decay energy of the system ^{4}H was completely confirmed in measurements at $E_{^6\mathrm{Li}} = 93$ MeV (see Fig. 2b). This shows that the value found for the mass of the quasistationary ^{4}H nucleus is reliable. The continuous distributions in the spectra of the ^{8}B nuclei at $E_{^6\mathrm{Li}} = 85$ and 93 MeV are described well by the curves of the three-particle phase space of the system $^8\mathrm{B}+t+n$, which are indicated by solid lines in Figs. 2a and 2b.

In summary, as a result of studying the reactions D(^{6}He, α) and ^{6}Li(^{6}Li,^{8}B) we obtained a new value for the ^{4}H mass defect, equal to 25.3 ± 0.3 MeV, and we observed an excited state of this nucleus with the decay energy $\varepsilon = 5.2 \pm 0.5$ MeV and the tentative configuration $(d + {}^2n)$ with the quantum characteristics 1^+.

This work was supported by grants from the Russian Fund for Fundamental Research and the International Science Fund (N91000).

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Translated by M. E. Alferieff