Possible observation of an excited state of the ^{3}H nucleus in the reaction H(^{6}He,α)

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Cross sections for the reaction (^{6}He,α) at H and ^{12}C nuclei and for the reaction H(^{6}He,^{6}Li) have been measured at an energy $E_{^6\mathrm{He}}=19.3$ MeV, for the first time. The spectrum of α particles from the reaction H(^{6}He,α) contains, in addition to the ground state of the triton, a resonance with an energy $E^*=7.0\pm0.3$ MeV and a width $\Gamma=0.6\pm0.3$ MeV. This resonance lies above the threshold for the dissociation $t\rightarrow n+d$. It is suggested that this level has a (^2n+p) configuration.

Substantial progress in producing secondary beams of radioactive nuclei has been made in recent years. Such beams have made it possible to measure the total cross sections for interaction of the ^{6}He, ^{8}He, and ^{11}Li nuclei. These cross sections have proved to be unusually large.[1] Later experiments found that a "neutron halo"[2] exists in such nuclei as ^{11}Li and ^{11}Be.

Active research in secondary beams, at energies from a few tens to hundreds of MeV per nucleon, is presently being carried out. Also clearly of interest are experiments at low energies, at which it is possible to carry out spectroscopic studies of reactions caused by radioactive nuclei. In this energy region we should expect to see unique properties of projectile nuclei with a large neutron excess, e.g., large cross sections for the transfer of valence neutrons.

We have undertaken an effort to produce a secondary beam of ^{6}He ions with an energy of 3–4 MeV/A and to study the reaction (^{6}He,α) involving light target nuclei. The reason for the particular interest in the nucleus ^{6}He is that the binding energy of the last two neutrons in ^{6}He is anomalously low, 0.97 MeV, while the corresponding figures for stable nuclei, e.g., ^{9}Be and ^{12}C, are 20.6 and 31.8 MeV, respectively. The small binding energy and the relatively large pairing energy of the two neutrons suggest that an interaction of ^{6}He with nuclei at low energies will be dominated by the mechanism of a direct transfer of a dineutron as a cluster. This suggestion is supported by the theoretical work of Ref. 3, in which it is shown that ^{6}He contains a clearly defined configuration of an α particle plus a dineutron.

To produce the secondary ^{6}He beam we selected the reaction ^{14}C(^{7}Li,^{6}He)^{15}N. The ^{7}Li ions, accelerated to an energy of 25 MeV at the cyclotron of the Kurchatov Institute Russian Science Center, struck a ^{14}C target 1.3 mg/cm^2 thick, with an 80% enrichment. The reaction products were analyzed and focused at a secondary target with the help of the MASÉ magnetic separator.[4]

The rigidity of the dipole moments of the MASÉ was adjusted for a maximum transmission of ^{6}He nuclei. A "degrader," specifically, a foil of a Mylar-like material

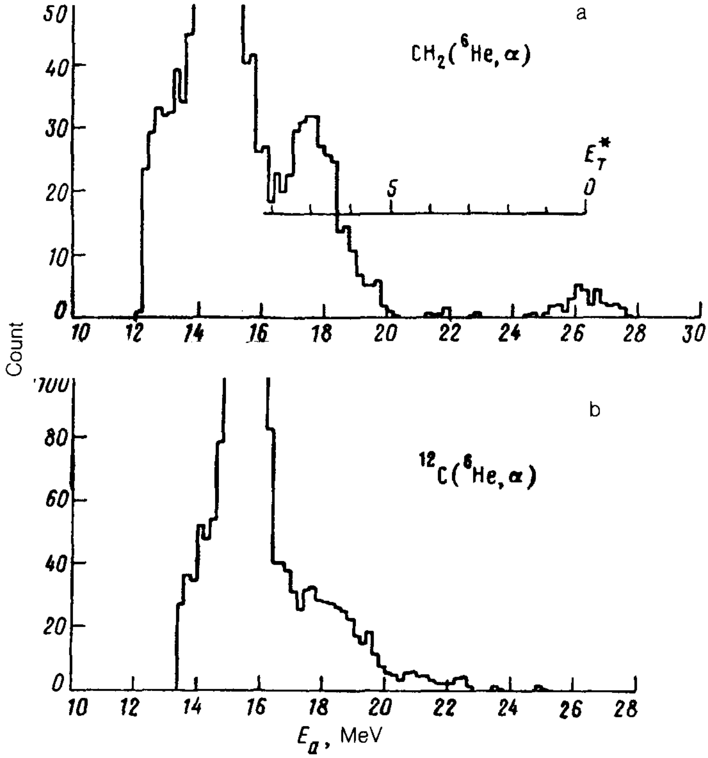

FIG. 1. Energy spectrum of α particles from the reaction (^{6}He,α), measured at an angle of 6.3° at two targets: a—CH_2; b—^{12}C.

50 μm thick, was placed between the analyzing dipole and the collecting dipole in order to reduce the admixture of accompanying particles having the same magnetic rigidity. As a result, a beam of ^{6}He ions with an energy of 20.8 MeV, a resolution of 0.9 MeV, and an intensity of 2×10^3 particles/s was produced. The diameter of this beam at the secondary target was 6 mm, the admixture of tritium ions was $\leqslant$ 2%, and that of α particles was $\leqslant 10^{-3}$%.

The system for identifying the reaction products consists of two semiconductor ΔE detectors, each 30 μm thick, and an E detector, with a diameter of 5 cm. The central region of the E counter is protected from the direct beam by a tantalum shield 3 cm in diameter. The energy spectra are measured in an annular geometry at an angle of 6.3 ± 1.3°. The solid angle of the detection system is 3.1×10^{-2} sr.

We first studied the reaction (^{6}He,α) at hydrogen and carbon nuclei. The targets were films of polyethylene and carbon, with respective thicknesses of 6.6 and 7.3 mg/cm^2.

Figure 1a shows the spectrum of α particles from the (^{6}He,α) reaction at the CH_2 target. The peak at 26.5 MeV in the hard part of the spectrum can be identified unambiguously as the ground state of the triton, which is populated in the $H(^6He,\alpha)$ reaction. Its cross section in the c.m. frame is $d\sigma/d\Omega = 14$ mb/sr. In addition to this peak, there is a clearly defined resonance at 17.5 MeV. An attempt to explain this peak on the basis of carbon in the CH_2 target was abandoned after measurements of the $(^6He,\alpha)$ reaction at the carbon target (Fig. 1b). It can be seen from this figure that the resonance at 17.5 MeV is missing. The slight increase in the count rate in this part of the spectrum should be attributed to an admixture ($<10\%$) of hydrogen in the carbon target. The particular method used to prepare this target—pyrolysis of methane—would allow such a hydrogen concentration in the carbon film.

Further measurements of the spectra of α particles from the reactions $(^6He,\alpha)$ at ^9Be and ^{28}Si showed that the yields of the $(^6He,\alpha)$ reaction at these targets are smaller by a factor of several tens than the $H(^6He,\alpha)$ cross section. Consequently, the resonance at $E_\alpha = 17.5$ MeV cannot be attributed to small admixtures in the CH_2 target.

We also note that there is a large increase in the number of events on the left side of the spectrum at $E \approx 15$ MeV in Figs. 1a and 1b. This effect arises because of the incomplete collection of charge from elastically scattered ^6He nuclei in the E detector.

We know that the appearance of resonance-like structures in the spectra of reaction products can also be explained on the basis of two-step processes. In the interaction of ^6He with hydrogen, the following reactions, which go in two steps, are possible:

1) $^6He + p \rightarrow d + {}^5He \rightarrow \alpha + n,$

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

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

A kinetic analysis made it possible to rule out the first two of these processes, because the positions and widths of the calculated peaks disagree with the observed values. The calculations were carried out by the SPEC program (written by H. G. Bolen, of the Hahn–Meitner Institute in Berlin). The anisotropy of the reaction channels and the geometry of the detection system are taken into account in this program. A kinematic analysis for the quasielastic-transfer reaction $^6He + p \rightarrow n + {}^6Li^*$ does not unambiguously rule out the appearance of a resonance in the spectrum of α particles from the decay $^6Li^* \rightarrow a + d$. We accordingly carried out some special measurements of the $H(^6He,{}^6Li)n$ reaction under the same conditions. It turned out that the yield of the reaction resulting in the production of ^6Li in the ground state is smaller by a factor of 4 to 5 than the probability for the filling of the resonance at $E_\alpha = 17.5$ MeV. The minimum angular-momentum transfer in the $H(^6He, {}^6Li_{g.s.})$ reaction is $L=0$. In the case of excitation of the 2.18-MeV level (3^+) in ^6Li, the reaction occurs with a minimum angular momentum $L=2$. An estimate of the centrifugal barrier $B_{cen} = \hbar^2 L(L+1)/2\mu R^2$ for the $^6He + p$ system with $L=2$ yields $B_{cen} \simeq 9$ MeV at $R = 4$ fm, while the energy of the $^6He + p$ interaction in the c.m. frame is $E = 2.7$ MeV. The 3^+ level in $^6Li^*$ is thus excited more weakly than the ground state by a penetrability factor $T_{L=2} = 0.2$. Consequently, the peak at $E_\alpha = 17.5$ MeV cannot be explained on the basis of these two-step processes.

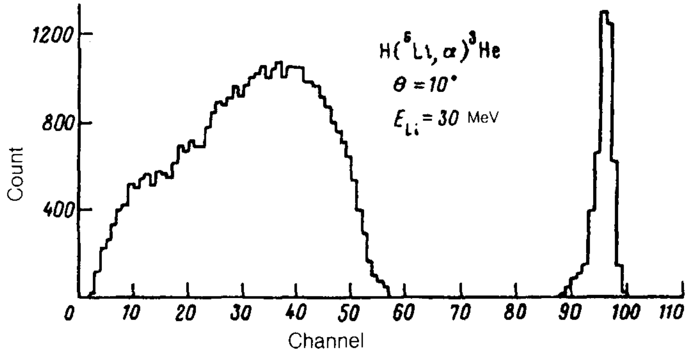

FIG. 2. Energy spectrum of α particles from the reaction H(^{6}Li,α)^{3}He, measured at $E_{^6Li}=30$ MeV.

We have suggested that a previously unknown excited state of the tritium nucleus, with an energy $E^*=7.0\pm0.3$ MeV and a width $\Gamma=0.6\pm0.3$ MeV, is filled in the reaction H(^{6}He,α)T, with a cross section $d\sigma/d\Omega=36\pm6$ mb/sr (c.m.). Figure 1a shows the energy scale of the triton excitation. The existence of a level in T, lying 0.5 MeV above the threshold for the $n+d$ decay, has been predicted in several theoretical papers (see, for example, the review[5]).

To explain the nature of this level, we used a gaseous target to measure the reaction H(^{6}Li,α) at an energy $E_{\rm Li}=30$ MeV, in which there is a high probability for the transfer of a deuteron as a cluster.[6] If this state in T has the $(d+n)$ configuration, then a corresponding level of the $(d+p)$ structure, within Coulomb corrections, should occur in the mirror nucleus ^{3}He. Figure 2 shows the spectrum of α particles from the reaction H(^{6}Li,α)^{3}He. In addition to the peak corresponding to the ^{3}He ground state, we see a broad, continuous distribution associated with the dissociation of ^{6}Li. No such features indicating the existence of an excited state in ^{3}He were observed. On the basis of the discussion above and the suggestion that the mechanism of the transfer of a dineutron is predominant in the (^{6}He,α) reaction, we can conclude that the level with $E^*=7.0$ MeV in T corresponds to a (^2n+p) configuration. Further evidence in favor of this hypothesis comes from the absence of the resonance from the energy dependence of the total effective cross section for the scattering of a neutron by a deuteron.

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