CATALYSIS OF THE $d + d \rightarrow He^3 + n$ FUSION REACTION BY NEGATIVE MUONS

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Twenty cases of the hitherto unobserved reaction (2) were registered in a diffusion chamber filled with deuterium to a pressure of 7.2 atm. The yield of this reaction (2) relative to the yield of reaction (1) amounts to 1.20 ± 0.37. The estimates of the relative yields of reactions (3) and (4) show, with a probability 90%, that $w(3)/w(1) < 0.13$ and $w(4)/w(2) < 0.13$. The yield of reaction (1) agrees with the data which we obtained earlier [4], but the yields of the reactions (1) and (2) in our experiments were approximately one order of magnitude higher than those expected on the basis of data on the reaction (1), obtained in liquid deuterium by several workers [3,5].

It is known that negative muons stopped in deuterium produce $d\mu$ mesic atoms and then, as a result of the formation of $dd\mu$ mesic-molecule ions, they can catalyze the following fusion reactions[1)]:

$$d\mu + d \rightarrow dd\mu \rightarrow \begin{cases} t + p + \mu^- & (1) \\ He^3 + n + \mu^- & (2) \\ p\mu + t & (3) \\ He^3\mu + n & (4) \\ t\mu + p & (5) \end{cases}$$

Information on the yield of reaction (1) was obtained in many experimental investigations [2-5].

The purpose of the present paper, which continues a cycle of researches on mesic-atom processes in gaseous hydrogen [4,6], was the detection of the hitherto observed reaction (2). The experimental setup made it possible also to register reaction (1) and to obtain some estimates of the yield of reactions (3) and (4). Estimates of the yield of reaction (5) call for additional data reduction and will be published later.

As in the past, the experiment was carried out with the aid of a 380 mm diameter diffusion chamber placed in a 7,000 Oe magnetic field. Since the charged products of reactions (2)—(4) have low energies (several MeV), the pressure of the gas in the chamber ($94\% \ D_2 + 6\% \ H_2$) was reduced to 7.2 atm to increase the ranges. The gas employed was rid of tritium impurities to a concentration 5×10^{-12} atomic percent, and also of possible impurities of other gases to a concentration less than 0.01 atomic percent. The working liquid was normal propyl alcohol C_3H_7OH, which ensured a total concentration of less than 0.1 atomic percent carbon and oxygen atoms in the fiducial volume of the chamber.

A double scanning of 33,800 stereo photographs yielded 3,340 stopped negative muons. A total of 21 events of reaction (1) was registered. Events of this reaction can be readily identified by the tritium and proton ranges, and also by the angle between them, which was equal to 180°, within the limits of measurement error.[2)] Only in 5 cases of reaction (1) was there a clear cut decay-electron track emerging from the point where the nuclear reaction took place. The reason for it was that the low vapor tension of the propyl alcohol made the efficiency for registering the electrons from the muon decay only 33% in this experiment.

In view of the relatively low efficiency of electron registration, cases of reactions (2)—(4) can frequently have only a track of one secondary charged particle and consequently have the same appearance as the single-prong stars due to the capture of muons by carbon or oxygen nuclei. Therefore, in order to separate the cases of two-particle reactions (2)—(4) of interest to us, in

1)The probability of reactions without the intermediate stage of formation of the $dd\mu$ mesic-molecule ion should according to[1] be appreciably lower.

2)Owing to the relatively weak bond of the muon in the $dd\mu$ system, almost the entire reaction energy is distributed among the heavy particles t and p [or He^3 and n in reaction (2)], and therefore both reactions can be regarded with great accuracy as being two-particle reactions.

which the charged particles have a strictly determined range, we plotted the distribution of the single-prong stars by the ranges of the secondary particles (Fig. 1a). The only cases considered in the distribution were those for which the projection of the secondary-particle track was more than 1 mm long, and the angle between the direction of the muon track at the stopping point and the track of the secondary particle was included in the 20—160° range. The distribution included also the four cases in which a decay electron track was observed along with the track of the heavy secondary particle.

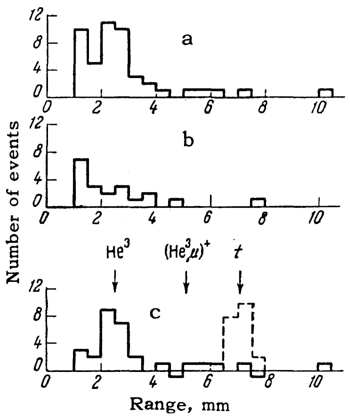

FIG. 1.

To take into account the background of the single-prong stars from the capture of the muons by the carbon and oxygen nuclei, we used data from another experiment, in which the chamber was filled with hydrogen to 5 atm pressure, and the number of stopped muons was the same as in the present experiment (with deuterium). Figure 1b shows the range distribution of the secondary particles, recalculated to a pressure of 7.2 atm, in the single-prong stars of the hydrogen experiment. Since the total number of starts with visible prongs due to muon capture by nuclei was almost the same in both experiments (21 and 17 in the experiments with D_2 and H_2, respectively)[3)], we could take into account the background by a procedure wherein the distribution shown in Fig. 1b was subtracted from the distribution shown in Fig. 1a. The range distribution so obtained is shown in Fig. 1c. The arrows indicate here the calculated values of the He^3 ranges for reaction (2), the ranges of $(He^3\mu)^+$ for reaction (4) and of t for reaction (3). The dashed lines in the same figure show the measured range distribution of the tritium nuclei from reaction (1). It is seen from Fig. 1c that, taking into account the experimental resolution of the He^3 line, 20 cases with an approximate secondary-particle range 2.5 mm can be attributed to the reaction (2). This number includes also the above-mentioned four cases with the decay electron. A photograph of one such case of the reaction d + d → He^3 + n, catalyzed by a muon, is shown by way of illustration in Fig. 2.

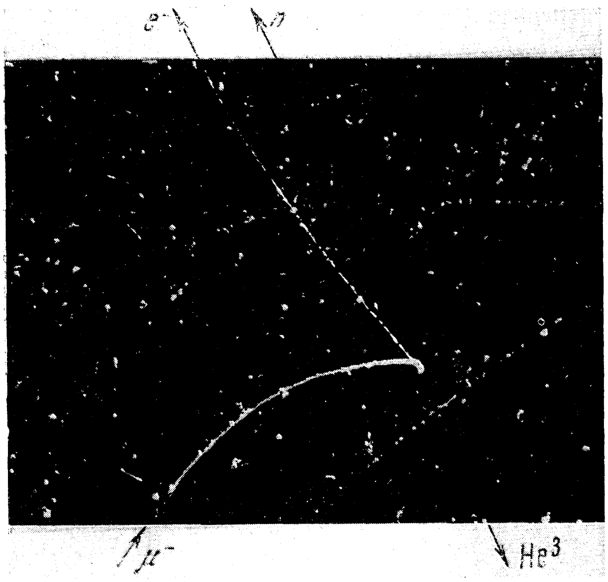

FIG. 2

The ratio of the yields of reactions (1) and (2), after introducing corrections for the efficiency of registration of reaction (2), is, as expected, approximately equal to unity

$$w(dd\mu \to He^3 + n + \mu^-) \,/\, w(dd\mu \to t + p + \mu^-)$$
$$= 1.20 \pm 0.37.$$

Reactions (1) and (2) proceed in the ddμ mesic molecule at low energies, and the observed ratio of the yield is in agreement with the data on the relative yield of the reaction D(d, n)He^3 and D(d, p)H^3, obtained in accelerating tubes at the minimum investigated deuteron energies 4—20 keV [7].

On the basis of the experimental range distribution we can also estimate the upper limits for the yields of reactions (3) and (4). Assuming, as can be seen from Fig. 1c, that the number of the cases for each of the reactions does not exceed unity, we can state with a probability of 90% that

$$w(dd\mu \to He^3\mu + n) \,/\, w(dd\mu \to He^3 + n + \mu^-) < 0.13,$$
$$w(dd\mu \to p\mu + t) \,/\, w(dd\mu \to t + p + \mu^-) < 0.13.$$

[3)]These numbers of stars include, along with many-prong stars, only those single-prong stars in which the range of the secondary particle exceeds 8 mm.

Theoretical estimates [1,8] yield for these ratios ~0.13 and ~0.01, respectively.

It must be noted that the value 35% for the yield of reaction (1), determined in the present investigation with allowance for the probability of the transfer of the muons from the deuterons to the complicated nuclei, agrees with the previously obtained yield of these reactions at a deuteron pressure of 16 atm in the chamber [4]. However, the yields of reactions (1) and (2) in our experiments were approximately one order of magnitude higher than those which can be expected on the basis of the data on the yield of reaction (1) in liquid deuterium [3,5] (assuming 100% probability of the nuclear reaction in the $dd\mu$ mesic molecule). So far we have not found a satisfactory explanation for this difference.

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304