Search for the Radiative Capture Reaction $d + d \rightarrow ^4$He + $\gamma$ from the $dd\mu$ Muonic Molecule State*


Received January 15, 2002; in final form, April 25, 2002

Abstract—A search for the muon-catalyzed fusion (MCF) reaction $d + d \rightarrow ^4$He + $\gamma$ in the $dd\mu$ muonic molecule was performed using the experimental MCF installation TRITON and NaI(Tl) detectors for $\gamma$ quanta. A high-pressure target filled with deuterium was exposed to the negative muon beam of the JINR phasotron to detect $\gamma$ quanta with an energy of 23.8 MeV. The first experimental estimation for the yield of radiative deuteron capture from the $dd\mu$ state $J = 1$ was obtained at a level of $\eta_{\gamma} \leq 2 \times 10^{-3}$ per one fusion.

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1. INTRODUCTION

It is understood that investigations of fusion reactions between hydrogen isotope nuclei at low energies are of great importance for determining properties of the lightest nuclei and for astrophysics. In particular, there is a need for new or improved measurements of many radiation capture reactions included in various astrophysical scenarios. Due to the Coulomb repulsion fusion, cross sections $\sigma(E)$ drop rapidly at low ($E \leq 100$ keV) collision energies (in an exponential scale for “bare” nuclei).

The reaction

$$d + d \rightarrow ^4\text{He} + \gamma + 23.8 \text{ MeV} \quad (1)$$

is involved in both primordial and stellar nucleosynthesis. Its cross section is rather small (about 1 pb at 50 keV, compared to 1 mb for the main fusion channels $d(d, n)^3$He and $d(d, p)^3$H), and its experimental investigations in $dd$ collisions are rather difficult.

At energies $E > 400$ keV, reaction (1) proceeds mainly by a $d$-wave $E2$ transition to the $^1S_0$ state of $^4$He [1]. The reason is the identical boson character of the entrance channel requiring $L + S$ to be even ($L$ and $S$ are the orbital angular momentum and the total spin of the $dd$ system). At lower energies, the centrifugal barrier suppresses the $d$-wave $E2$ capture, allowing an $s$-wave $E2$ transition to the $D$-state admixture of $^4$He. Measurements extended to energies below 100 keV [2] have confirmed this picture. However, the existence of multipoles other than $E2$ in reaction (1) was not excluded experimentally despite the belief that dipole transitions $E1$ and $M1$ with $\Delta S = 0$ should be suppressed due to the standard isospin selection rule $\Delta T = 0$.

Measurements of cross section angular distributions $\sigma(\theta)$ of vector $A_y$ and tensor $A_{yy}$ analyzing powers performed with a polarized deuteron beam with an energy of $E_d^{\text{lab}} = 80$ keV stopping in the target have yielded an unexpected observation of the $p$ wave strength in $^2$H($d, \gamma)^4$He reaction [3]. It was found that over 50% of the cross section strength at these low energies were due to $E1$ and $M2$ $p$ wave capture. This finding might be considered as a violation of the isospin selection rule and affect the low-energy behavior of the total cross section and its extrapolation to substantially sub-Coulomb energies (as required, e.g., by stellar calculations). Other evidence for non-$E2$ radiation can be found in [3]. It would be extremely interesting to observe any direct manifestation of the $p$ wave in an independent measurement.

During recent decades, experiments in which various fusion reactions between hydrogen isotopes are
catalyzed by muons have provided supplementary information about these reactions at energies well below the lowest energies accessible by conventional beam–target experiments [4]. In the muon-catalyzed (MC) process, fusion takes place from the bound states of muonic molecules. Nuclei inside muonic molecules are practically at rest, being separated by average distances \( a_\mu \sim \hbar^2/e^2m_\mu^2 = 2.5 \times 10^{-11} \) cm (\( m_\mu \) is the muon mass).

Muonic molecules can be formed in states with total angular momenta \( J = 0 \) and \( J = 1 \) that correspond to the relative orbital angular momenta of nuclei \( L = 0 \) and \( L = 1 \). Depending on the hydrogen-isotope-mixture parameters, various states of muonic molecules can be populated. This makes it possible to study fusion reactions at superlow energies from prepared molecules instead of \( \alpha \)-particles, \( \alpha \)-fragmentation, and various states of muonic molecules. Nuclei inside muonic molecules are mainly formed in the \( J = 1 \) state and fusion reactions proceed from the \( p \) wave of relative nuclear motion. Hence, if detected, 23.8-MeV \( \gamma \) quanta would unambiguously indicate a finite \( p \) wave contribution to the rate of process (4).

In view of this, we investigated the possibility of process (4) being detected in our last measurements of the \( dd\mu \)-molecule formation rate [10]. For this aim, one of two usually used neutron detectors [11] was removed and a gamma detector was installed instead. The level of the radiation background in our installation was measured. We present the first experimental estimation for the yield of the \( p \) wave radiative \( dd \) capture from the \( dd\mu \) molecule.

2. EXPERIMENTAL METHOD

The experimental setup (its layout is shown in Fig. 1) is described in detail in [12]. A high-pressure deuterium target (HPDT) [13] was exposed to the muon beam of the JINR phasotron. Scintillation counters 1–3 in front of the HPDT detected the incoming muons. Cylinder-shaped multiwire proportional chambers 4 and 5 served to identify the muon stop in the target and to detect electrons from muon decay. A coincidence between signals of counters 5 and 1, 2 served as the electron signal.

A full absorption neutron detector (ND) (volume of NE-213, \( v = 12.5 \) l) [12, 14] was aimed to detect neutrons from reaction (2). To reduce the background, \( n - \gamma \) separation was realized by comparing the signals for the total charge and the fast component charge of the ND pulse. The efficiency of the \( \gamma \)-quantum discrimination was better than \( 10^{-3} \) for energies \( E_\gamma < 100 \) keV.

The \( \gamma \) quanta were detected with a NaI(Tl) crystal of 150-mm diameter and 100-mm height. It was calibrated with \( \gamma \) sources of \( ^{60}\text{Co} \) (total energy of two \( \gamma \)’s...