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E1-90-321

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THE POSSIBILITIES OF THE EXPERIMENTAL INVESTIGATIONS OF THE SPIN EFFECTS IN THE ddμ MOLECULE FORMATION AT THE DEUTERIUM PRESSURE 1.5 KBAR. THE FIRST RESULTS

Submitted to International Conference on Muon Catalyzed Fusion, Austria, Vienna, May 27 - June 1, 1990

1990

The dependence of the ddμ-molecule formation rate ($\lambda_{dd\mu}$) on the dμ-atom spin state can be considered a bright manifestation of the resonant character of the muonic molecule formation process[1-9]. The investigation of this phenomenon is of great importance since it allows the precise determination of the energy of a weakly bound level with J=v=1 in the ddμ-system and gives the possibility of testing the principal features of the theory of the resonant muonic molecule formation process.

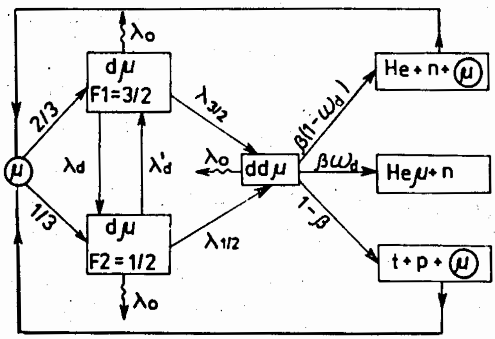

Fig.1. Scheme of μ-atomic and μ-molecular processes in deuterium.

A scheme of the main process caused by negative muons in deuterium is shown in fig.1. The dμ-atoms are initially formed in two states of hyperfine structure with a spin F=3/2 and F=1/2. The transitions from the upper spin state to the lower spin state can take place in the collisions of dμ-atoms with deuterium atoms (molecules). At low deuterium temperatures (to 100 K) these transitions are irreversible. From each dμ-atom spin state the ddμ-molecule can be formed, which also has two states with a total spin S=3/2, 1/2. So there are four (if one neglects the rotationl structure) resonances which correspond to different deuterium temperatures. Hence the ddμ formation rates from the two dμ-atom spin states ($\lambda_{3/2}$ and $\lambda_{1/2}$) as a function of deuterium temperature must be different. This difference especially manifests itself at low temperatures where the ratio $\lambda_{3/2}$ / $\lambda_{1/2}$ can be 70-80.

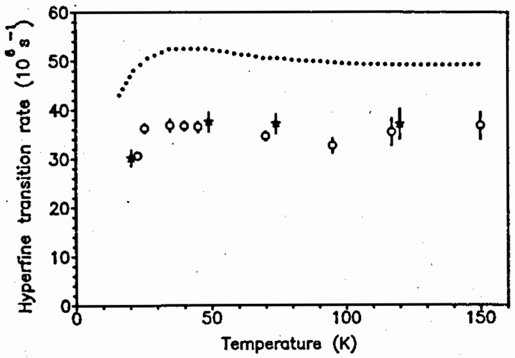

Fig.2. Temperature dependence of the rate of transitions $F_{d\mu}(3/2) \longrightarrow F_{d\mu}(1/2)$. Experimental data: ○ results[9,10], ★ -present work. Line -calculations[13] performed with allowance for the back decay of the mesomolecular complex $[dd\mu,d,2e]^*$ (taken from work[9]).

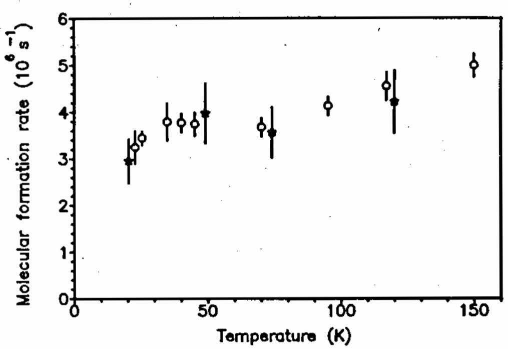

Fig.3. Results of the measurement of the temperature dependence of the values $\lambda_{3/2}$. Open points -data[9,10], dark points -present work.

The effect of spin dependence of the $dd\mu$-molecule formation rate was experimentally discovered by the Vienna-PSI group[7,8]. In further experiments of this group [9,10] the values of $\lambda_{3/2}$ and $\lambda_{1/2}$ as well as the rate λ_d of the transition $F=3/2 \longrightarrow F=1/2$ were measured as a a function of deuterium temperature. These measurements were performed with liquid deuterium at T=21.5 K and with gaseous deuterium of relatively small density: ϕ=2%, 4% (relative to the liquid hydrogen density n=4.25x10^{22} nucl/cm^3) in the temperature region T=25-150 K. The results[9,10] are shown in figs. 2 and 3. After fitting their data on the $\lambda_{3/2}(T)$ and $\lambda_{1/2}(T)$ according to the theory [5,6,11] the authors[9,10] could determine the energy of the weakly bound level J=v=1 in the $dd\mu$-molecule with a very high accuracy: $\varepsilon_{J=v=1}$ =-1965.9(0.5) meV. This value is in agreement with the calculations: $\varepsilon_{J=v=1}$ =-19664.3 meV[12] with an accuracy 1 meV. As to the value of λ_d, the experimental data [9,10] are smaller to 40% than it follows from calculations[13] with allowance for the change of the $d\mu$-atom spin state due to the back decay[14] of the complex $[dd\mu,d,2e]^*$ which includes the $dd\mu$-system at its resonant formation.

At the present conference we present the talk[15] which is devoted to the study of the process of the $dd\mu$-molecule formation rate at a high deuterium density ($\phi\cong1$) in the temperature region T=20-300 K. The main aim of the experiment[15] was to measure the dependence $\lambda_{1/2}$ (T). No special efforts were made to accurately determine the values of $\lambda_{3/2}$ and λ_d. Taking into consideration the great importance of the knowledge of these values namely for a high deuterium density, where the theory[6] predicts interesting density effects, we have made an attempt to estimate the values of λ_d and $\lambda_{3/2}$ on the basis of the data obtained in work[15]. It is important that in this case the problems were clarified (selection of events, time calibration etc.) which had to be solved for the accurate measurement of the value of $\lambda_{3/2}$ and λ_d. Now this experiment with improved method is under way. The preliminary results obtained from the analysis of the data[15] are presented here.

The experimental method is described in our works[15,16]. Its principal features are the use of the gaseous deuterium target of high pressure (1.5 Kbar)[17] and two scintillation neutron spectrometers (full absorption detectors)[18]. These detectors are located symmetrically around the target; they were to detect the neutrons from the fusion reaction

$$dd\mu \longrightarrow {}^3He + n + \mu + 2.45\ MeV. \qquad (1)$$

The main problem which we had to solve for reliable detection of the fast transitions 3/2 —— 1/2 (λ_d/ϕ = 30-40 μs^{-1}) was suppression of the background events arising from muon stops followed by nuclear capture in the target wall material (Ni,Cr). Under our experimental conditions (the muon beam parameters, target wall thickness) the part of muons stopped in deuterium was only a few percent relative to all muon stops in the target. The powerfull criterion for background suppression was the requirement to detect both the neutron from reaction (1) and the electron from the decay of the muon stopped in the target - delayed n-e coincidences - in the time interval 10 μs after the muon stop. An additional criterion was the limitation of the electron detection time: $t_n + 0.2\mu s < t < t_n + 2.2\ \mu s$, where t_n is the neutron detection time.

The measurements have been performed with liquid and gaseous deuterium. The parameters of the main exposures are presented in the table. The exposures with helium and with an empty target were performed to determine the neutron and electron background. For each exposure the time distributions of the first detected neutrons were created and analysed. The data for each neutron detector were analysed separately. The example of the neutron time distribution obtained in the exposure with liquid deuterium is shown in fig.4.

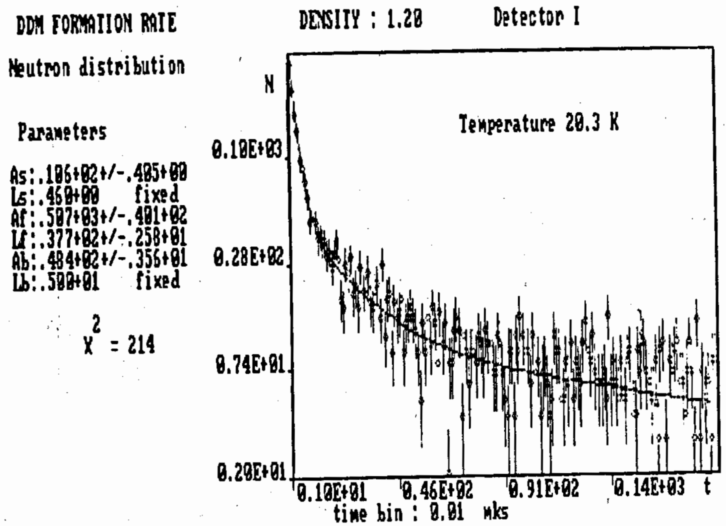

Fig.4. Experimental time distribution of the first detected neutron events measured in the exposure with liquid deuterium. Line -dependence (2) with optimal parameters.

The neutron time spectra were analysed using the expression

$$dN_n/dt = C\cdot(A_f \exp(-\lambda_f t) + A_s \exp(-\lambda_s t)) + F_b(t), \qquad (2)$$

where C is the normalization factor; A_f and A_s are the amplitudes of the fast and the slow component, λ_f and λ_s are the corresponding exponential factors, F_b is the function of the time distribution of the background events (the neutrons from muon capture in the target walls and random coincidences). As it follows from papers[5-9,19] ,

$A_s \cong \beta\phi\lambda_{1/2}$, $A_f \cong 2/3\, A_s\cdot(\lambda_{3/2} - \lambda_{1/2})$, $\lambda_f \cong \lambda_d$,

$\lambda_s = \lambda_o + (\varepsilon + \omega - \varepsilon\omega)\cdot\beta\phi\lambda_{1/2}$, $\lambda_o = 0.455\ \mu s^{-1}$ is the muon disappearance rate, $\omega = 0.126+0.004$ [19] the probability of muon sticking to helium in reaction (1), $\varepsilon = 0.142+0.006$ -the neutron detection efficiency, β is the partial probability of reaction (1). For the resonant formation (J=1) β=0.58[20] , and for nonresonant formation β=0.53[21] .

From the accurate consideration of the processes, shown in fig.1, it follows that the values of A_f, A_s, λ_f are functions of the parameters $\lambda_{3/2}$, $\lambda_{1/2}$, λ_d, β, ω and ε. The expressions for these functions[5,19] were used in the analysis. For the amplitude of the slow component we took the values found in our work[15] . To avoid the influence of the distortions in the time distribution due to the finite time resolution of the neutron detector (10 ns) we analysed the neutron events starting from the initial time 20-30 ns after the zero time.

In the experiment[15] we could not ensure the time calibration with an accuracy sufficient for the accurate determination of $\lambda_{3/2}$. To find the position of the zero time t_o for each neutron detector we have compared the yield of the second neutrons really detected in experiment with the yield which is expected if one takes into consideration only the slow component in time distribution (2) of the first detected neutrons. This procedure was made for the data obtained at low temperatures (T=20,49,74 K) where the relative part of the second detected neutrons caused by μCF from the upper dμ-atom state is expected to be especially large and can achieve 100%. (When the limitation $t_n^{second} - t_n^{first} > 0.2\ \mu s$ is used this effect should decrease approximately by a factor of two). As this part is proportional to the value of $A_f\lambda_s/A_s\lambda_f$, we could determine (using the value of λ_f and A_s from the fit) the value of t_o. These values of t_o found for the data of three above-mentioned exposures were averaged and then they were used in the analysis for normalization of the amplitude A_f.

The obtained values of λ_d and $\lambda_{3/2}$ (normalized to the liquid hydrogen density) are presented in the table and in figs. 2, 3.

Table.

The parameters of the experiment and the main results.

Relative deuterium density, ϕ	1.20	0.883			
Temperature, K	20.3	49	74	120	300
λ_d, μs^{-1}	30.2±1.6	37.6±2.0	37.3±2.0	37.2±3.1	43±18
$\lambda_{3/2}$, μs^{-1}	2.9±0.5	3.9±0.7	3.5±0.6	4.0±0.7	———

The uncertainties in the values of λ_d have been obtained from the fit. The uncertainties in the values of $\lambda_{3/2}$ are mainly due to statistical errors in the number of the second detected neutrons. Besides, there may be some systematic errors caused by the method of t_o determination. Therefore it is more reliable to consider our values of $\lambda_{3/2}$(T) from the point of view of their relative dependence on temperature. For the relative dependence $\lambda_{3/2}$(T) the uncertainties should be about 10%.

As seen from figs. 2, 3, there is agreement between our data and the results[9,10] both for λ_d and for $\lambda_{3/2}$. We intend to make the comparison with theory after the experiment with the improved method where these values should be accurately determined. At present this experiment is being performed.

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Received by Publishing Department

on May 10, 1990.

Фильченков В.В., Марциш Л. E1-90-321
Возможности экспериментального исследования спиновых эффектов в образовании ddμ-молекул при давлении дейтерия 1,5 кбар.
Первые результаты

На основе экспериментального материала, полученного в опытах по исследованию температурной зависимости скорости образования молекул ddμ, проанализированы возможности регистрации процесса переходов между уровнями сверхтонкой структуры dμ-атомов в дейтерии высокой плотности /жидком и газообразном при давлении 1,5 кбар/. Найдены оптимальные способы обработки экспериментальных данных, с их помощью получены предварительные данные о скорости указанных переходов, а также о скорости образования молекул ddμ из верхнего спинового состояния dμ-атома.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1990

Filchenkov V.V., Marczis L. E1-90-321
The Possibilities of the Experimental Investigations of the Spin Effects in the ddμ-Molecule Formation at the Deuterium Pressure 1.5 kbar. The First Results

Using the data obtained in the runs on the measurement of the temperature dependence of the ddμ-molecule formation rate the possibilities of detecting the transitions between the hyperfine states of ddμ-atoms in deuterium of high density (liquid and gaseous at the pressure 1.5 kbar) have been analysed. The optimal methods have been found for handling the experimental data. The preliminary results on the above transition rate and on the ddμ-molecule formation rate from the upper spin state of dμ-atom have been obtained.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna 1990