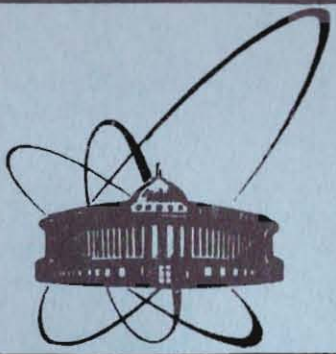

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E1-84-871

A.Guła, A.Adamczak, M.Bubak

BACK DECAY OF MUONIC MOLECULAR RESONANCES AND THE MEASURED VALUE OF dμd-FORMATION RATE IN MUON-CATALYZED FUSION IN DEUTERIUM

Submitted to "Physics Letters"

1984

INTRODUCTION

When a negative muon enters a deuterium target it forms a muonic deuterium atom $(d\mu)$ and subsequently a tightly bound $(d\mu d)^+$ system (r.m.s. $\sim 5 \cdot 10^{-11}$cm) in which the deuterons easily penetrate the Coulomb barrier and nuclear fusion results [1,2].

It is now well established that $d\mu d$ formation proceeds mainly via creation of a resonance μ-molecular compound [3-5]

$$d\mu + D_2 \rightarrow [(d\mu d)^+_{J,\nu} \cdot dee]^*_{K,v} \qquad (1)$$

in which the $d\mu d$-system is in a weakly bound ($\epsilon_b \sim 1.91$ eV) rotational-vibrational state $J = 1$, $\nu = 1$. The energies are tuned by the vibrational ($\epsilon_v \sim 10^2$ meV) and rotational ($\epsilon_k \sim 1$ meV) excitations of compound (1) and by a relative collision energy ($\epsilon_T \sim 10$ meV) [2,6]. It has been commonly assumed, so far, that - unless the muon decays - (1) leads inevitably to fusion. However, as pointed out in [7], a decay of the resonance compound (1) back into the formation channel may seriously compete with transitions followed by fusion in $d\mu d$. In this paper we investigate the consequences of this observation.

1. RESONANCE BACK DECAY AND MCF KINETICS

Figure 1 presents the main processes forming one muon-catalyzed fusion (MCF) cycle* in deuterium with inclusion of the resonance back decay (RBD). The most important transitions competing with RBD (dashed line) are [7]:

i) direct fusion in the $J = 1$, $\nu = 1$; K, v state of the compound,

ii) destruction of the resonance compound by deexcitation of $d\mu d$ to a lower $J = 1$, $\nu = 0$ state ($\Delta\epsilon_b \simeq 2 \cdot 10^2$ eV) and subsequent fusion,

iii) vibrational deexcitation of compound (1) in collisions with D_2 molecules. A $v \rightarrow v-1$ transition brings the compound below the elastic threshold ($\Delta\epsilon_v \gg \epsilon_T$). An implicit assumption

* When the deuterons fuse in $d\mu d$, the muon is mostly freed ($f \simeq 90\%$) and becomes available to catalyze another fusion.

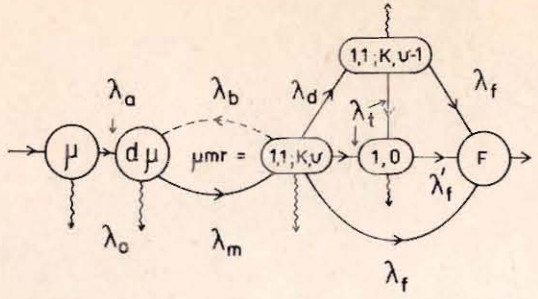

Fig.1. Kinetic graph presenting the processes forming one muon-catalyzed fusion cycle in deuterium. The μ , dμ and (1,0) nodes represent the muon, dμ - atom and dμd- ion in (J, ν) = = (1,0) state, (J, ν; K, v)- the μ -molecular resonance $[(d\mu d)_{J,\nu}\, dee]^{*}_{K,v}$. *F is a common vertex representing fusion in* dμd. *Wiggled arrows show muon decay.*

made in /7/ is that the rotational (K)-deexcitations which are relatively fast /8/ do not complete with RBD. This assumption is consistent with the strongly temperature dependent dμd-fusion data /3,5/ which can be well described by a single narrow resonance at $\epsilon_T = \epsilon_0 \simeq 50$ meV. Rotational excitations added to the required vibrational one ($\Delta\epsilon_K \ll \epsilon_v$) will leave the formation channel open in the ensuing K-transitions, thus, the general structure of the kinetic graph of Fig.1 will remain unchanged. (We shall return to this point below).

To see what is the effect of RBD on reaction kinetic let us consider the Laplace transform, $F_1(s)$ of the time distribution of fusion events ending the first cycle $F_1(t)$. Without RBD it reads /9,10/

$$F_1(s) = \frac{\Phi(s)}{\Lambda_\mu + s}\,\frac{\lambda_a}{\Lambda_{d\mu} + s}\,\frac{\lambda_m}{\Lambda_{\mu mr} + s}\,H(s), \qquad (2)$$

where λ_i are transition rates defined in Fig.1, $\Phi(s)$ represents the incoming muon flux, Λ_i are sums of transition rates over all lines leaving an i-th vertex (note that: $\Lambda_{1,1;K,v} = \Lambda_{\mu mr}$) and H(s) describes the structure of the subgraph linking the μmr and F nodes /11/ (channels leading to fusion in dμd):

$$H(s) = \lambda_f + \frac{\lambda_d}{\Lambda_{1,1;K,v-1} + s}\left[\lambda_f + \lambda'_f\,\frac{\lambda_t}{\Lambda_{1,0} + s}\right] + \lambda'_f\,\frac{\lambda_t}{\Lambda_{1,0} + s}\,. \qquad (3)$$

Inclusion of RBD leads to the following replacements in Eq.(2)

$$\Lambda_{d\mu} = \lambda_0 + \lambda_m \to R_{d\mu} = \lambda_0 + \frac{1}{2}(\lambda_m + \lambda_F + \lambda_b - \beta), \qquad (4a)$$

$$\Lambda_{\mu mr} = \lambda_0 + \lambda_F \to R_{\mu mr} = \lambda_0 + \frac{1}{2}(\lambda_m + \lambda_F + \lambda_b + \beta), \qquad (4b)$$

with

$$\beta = \sqrt{(\lambda_F + \lambda_b - \lambda_m)^2 + 4\lambda_b\lambda_m}\,, \qquad (4c)$$

$$\lambda_F = \lambda_e + \phi\lambda^\circ_d,\ \lambda_e = \lambda_f + \lambda_t,\quad \lambda_m = \phi\,\lambda^\circ_m, \qquad (4d)$$

where $\lambda_0 = 0.455\ \mu s^{-1}$ is muon decay rate, ϕ is target density expressed in units of liquid hydrogen density (LHD = $= 4.25\cdot 10^{22}\,cm^{-3}$) and index 0 denotes the collision rates normalized to LHD. Indeed, it is easy to verify that the $d\mu \rightleftarrows \mu mr$ loop created by RBD couples $\Lambda_{d\mu}$ and $\Lambda'_{\mu mr} = \Lambda_{\mu mr} + \lambda_b$ in the characteristic determinant of the set of the kinetic equations corresponding to the one-cycle graph in Fig.1, leaving the other Λ_i unchanged:

$$(\Lambda_{d\mu} + s)(\Lambda'_{\mu mr} + s) - \lambda_b\lambda_m = (R_{d\mu} + s)(R_{\mu mr} + s). \qquad (5)$$

2. DISCUSSION

Since the measurable characteristics of MCF: the time distributions of fusion events ending a k-th cycle and the corresponding total yields, are determined by $|F_1(s)|^k$ and $|F_1(0)|^k$ respectively /10,11/, practically all experimental results reported for temperatures, where process (1) dominates, have to be corrected for replacements (4). Since $R_{d\mu} < \Lambda_{d\mu}$ an immediate and most important comsequence is that the dμd formation rates Λ°_m obtained without taking RBD into account /3,4/ are underestimated.

The magnitude of the corrections depends on the ratio of λ_b to the sum of all transitions from the μmr-vertex: $\lambda_b + \lambda_F = \lambda_b + \lambda_e + \phi\lambda^\circ_d$. The formation and decay rates are proportional to each other, and upon averaging over the Maxwell distribution:

$$\lambda_b = \alpha(T)\cdot\lambda^\circ_m(T) \qquad (6)$$

with $\alpha(T) \simeq 300$ at T = 300-400 K /7,8/ - the temperature range where resonant formation (1) dominates /14/. With the latest experimental value of λ°_m (300K) $\simeq 3\ \mu s^{-1}$ /4,5/ it gives $\lambda_b \simeq 900\ \mu s^{-1}$, a value to be compared with $\lambda_f = 870\ \mu s^{-1}$ /15/, $\lambda_t = 190\ \mu s^{-1}$ /16/ and $\lambda^\circ_d \simeq 10\ \mu s^{-1}$ /7/ ($\lambda_d = \phi\lambda^\circ_d < \lambda^\circ_d$). However, as is shown below, with inclusion of RBD the experimental results for λ°_m have to be revised and a significantly stronger RBD-effect can be expected.

Indeed, if one requires for the data of /4/ ($\phi = 0.1$) that with Eq.(6) and the above values of α, λ_f, λ_t, λ°_d the large-time slope of the first-cycle time distribution, $F_1(s)$ which is $R_{d\mu}$ of Eq.(4a), should be reproduced by choosing appropriately λ°_m - one obtains: $\lambda^\circ_m = 12.6\pm1.7\ \mu s^{-1}$ instead of $2.76\pm$

$+0.08\ \mu s^{-1}$ obtained in [4] without taking RBD into account* ($\overline{R}_{d\mu} \to \Lambda_{d\mu}$). This value is much higher than the existing prediction [14] ($\sim 0.8\ \mu s^{-1}$). However, the results of [4,5] already challenge this estimate and further indications appear that the theoretical value of the μ-molecular resonance formation rate should be revised [6,17].

A nontrivial consequence of inclusion of RBD is that the formation rate determined from the large time slope of $d\mu d$ as, e.g., in [4]

$$\bar{\lambda}^{0}_{m} = (R_{d\mu} - \lambda_0)\phi^{-1} \qquad (7)$$

should vary with target density according to Eq.(4a) instead of being constant. Figure 2 shows $\bar{\lambda}^{0}_{m}$ as a function of ϕ for several values of λ^{0}_{d} and λ_e. A wide range of λ^{0}_{d} is covered to include the possibility that the rotational deexcitations also compete with RBD, as conjectured in [8]**. For each λ^{0}_{d} two hypotheses are tried: $\lambda_e = 10^3\ \mu s^{-1}$ [15,16] and $200\ \mu s^{-1}$, the latter being above the experimental lower limit on λ_F [3,12]. The experimental points are also shown: $\bar{\lambda}^{0}_{m} = 0.76 \pm 0.11$ ($\phi \approx 0.05$) [3], 2.76 ± 0.08 ($\phi = 0.103$) [4] and $\sim 3.0\ \mu s^{-1}$ ($\phi \approx 0.5$) [5].

As is seen from the figure, the results of [4] and [5] together imply $\lambda^{0}_{d} \sim 10^1 - 10^2\ \mu s^{-1}$ and $\lambda_e \sim 10^3\ \mu s^{-1}$. Even with ample errors of [5] this excludes much larger values of λ^{0}_{d} and, thus, supports the conclusion of [7] as opposed to [8] concerning the magnitude of the RBD effect, arrived at with similar values of α ($\simeq 300$).

On the other hand the result of [3] cannot be reconciled with the results of [4,5] with any reasonable choice of parameters. However, it should be remembered that different experimental approaches were used in determination of λ^{0}_{m} in all three experiments. We, therefore, do not conclude that our analysis supports the values of [4,5] in favour of the one obtained in [4] although the method of [4] seems to be the most straightforward and unambiguous (cf. [12]). We would rather suggest a systematic experimental investigation with inclusion of RBD. In particular,

* For simplicity we do not mention explicitly the contribution from transitions to impurities which in ref. [4] are small (cf. [12]) and do not change our estimate. (When necessary it should be added to $\Lambda_{d\mu}$ in (5)). The error of $1.7\ \mu s^{-1}$ corresponds only to the experimental error of [4]. We also make implicity the standard assumption [2-4] that the smallest Λ_i in Fig.1 corresponds to the $d\mu$-vertex (cf. [10]).

** In fact, λ^{0}_{d} for vibrational deexcitation depends strongly on the assumption used in its evaluation and a wide spectrum of values can also be expected [18].

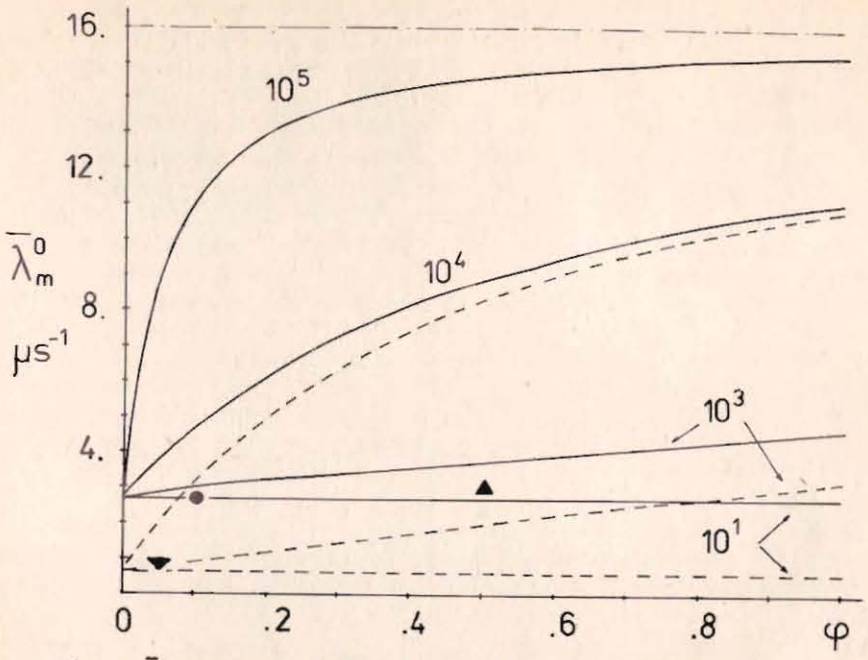

Fig. 2. $\bar{\lambda}^{0}_{m}$ vs target density ϕ (in units of LHD) for $\lambda^{0}_{m} = 16\ \mu s^{-1}$ and $\alpha = 300$. The values of λ^{0}_{d} are indicated at the curves. Solid lines correspond to $\lambda_e = 10^3\ \mu s^{-1}$ and the dashed ones to $200\ \mu s^{-1}$. The experimental points are: ▼ - Ref.[3], ● - Ref.[4], ▲ - Ref.[5].

an accurate measurement of $\bar{\lambda}^{0}_{m}(\phi)$ with a single experimental set-up could provide valuable information about the parameters involved. In particular, for large λ^{0}_{d} the value measured according to Eq.(7) would strongly increase with target density at small ϕ. So far, no such deviations from a linear dependence $\bar{\lambda}_m = \phi\lambda^{0}_{m}$ have been reported for $T \simeq 300K$. However, λ^{0}_{d} is expected to grow rapidly with T [7] (cf. [8]) and such an interesting effect may appear at somewhat higher temperatures.

Let us comment on some of the ambiguities which have not been mentioned above: If the rotational spectrum of the μ-molecular compound (and the initial D_2 molecules) is taken into account, appropriate averaging should be performed and the resulting value of α in Eq.(6) may become smaller [18] leading to a less pronounced RBD-effect. For example, with $\alpha = 100$ and other parameters as in Fig.2 the value of $\bar{\lambda}^{0}_{m} = 2.76\ \mu s^{-1}$ would lead to $3.8\ \mu s^{-1}$ instead of $16\ \mu s^{-1}$. However, a decrease of λ_e to $\approx 300\ \mu s^{-1}$ which - though much below the theoretical predic-

tion of [15] - is far from being excluded by the experimental data [3,12], would readily boost this value to $\approx 30\,\mu s^{-1}$. Also the hyperfine transitions between the $d\mu$-atom hf states should be included in a more refined study. The relevant formulae, though slightly more involved, can be written down straightforward, e.g., using the technique of [11]. However, at room temperature the hf transitions become pronounced in the time-distributions only at relatively small t whereas $R_{d\mu}$ is determined mainly by their large-time behaviour [12]. Nevertheless, only a systematic experimental survey especially at $T \geq 10^2$K and $\phi \leq 0.3$, can provide clues for resolving these ambiguities. Such study should present a particular interest as it could provide valuable input information for the analysis of MCF in $D_2 + T_2$ mixtures where RBD produces more complicated and rather nontrivial effect [19].

After this work has been completed we have learned that L.I.Menshikov has investigated the influence of RBD on the μ-molecular resonance formation rates. Using a probability argument for the "all-cycles" time distribution he obtained a formula for the correction factor by which the measured rates should be multiplied. For realistic values of the parameters his formula agrees with our Eqs.(7) and (4a) within a few per cent.

The authors are greatly indebted to L.I.Menshikov for very helpful discussions and indications. They also thank L.I.Ponomarev for constant encouragement and stimulating conversations and M.P.Faifman for his comments and remarks.

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Received by Publishing Department
on December 29, 1984.

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Гула А., Адамчак А., Бубак М.
E1-84-871

Распад μ-молекулярных резонансов и экспериментальное значение скорости образования $d\mu d$ в мюонном катализе ядерного синтеза в дейтерии

В работе показано, что пренебрежение в анализе экспериментальных данных по мюонному катализу ядерного синтеза эластическим распадом μ-молекулярного резонанса, образуемого в столкновениях $d\mu + D_2$ приводит к занижению скорости образования $d\mu d$. Предполагается эксперимент по определению некоторых важных параметров мюонного катализа ядерного синтеза в дейтерии.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1984

Guła A., Adamczak A., Bubak M.
E1-84-871

Back Decay of Muonic Molecular Resonances and the Measured Value of $d\mu d$-Formation Rate in Muon-Catalyzed Fusion in Deuterium

It is shown that neglecting the decay of the μ-molecular resonance produced in $d\mu + D_2$ collisions back into the formation channel in the analysis of the experimental data leads to underestimated values of the $d\mu d$-formation rate. An experimental investigation aimed at determination of some important parameters is suggested.

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

Preprint of the Joint Institute for Nuclear Research. Dubna 1984