Proposal for an experiment at the PSI Ring cyclotron (μE4 channel)

Measurement of Nuclear Fusion Reactions in $\mu d\,^3$He and $\mu d\,^4$He Molecules

R. Jacot-Guillarmod[S], F. Mulhauser[S], L.A. Schaller, L. Schellenberg,
H. Schneuwly, S. Tresch
Institut de Physique de l'Université, Fribourg, Switzerland

V.M. Bystritsky[S], V.B. Belyaev, V.G. Grebenyuk, V.I. Korobov,
V.I. Sandukovsky, V.T. Sidorov, V.A. Stolupin
Joint Institute for Nuclear Research, Dubna, Russia

C. Petitjean
Paul Scherrer Institute, Villigen PSI, Switzerland

A.V. Kravtsov
St.-Petersburg Nuclear Physics Institute, Gatchina, Russia

N.P. Popov
Sektion Physik der Universität München, München, Germany

M. Filipowicz, J. Woźniak
Institute of Physics and Nuclear Techniques, Cracow, Poland

1. Scientific justification

Many atomic and molecular processes may be induced when a negative muon is stopped in a mixture of hydrogen isotopes. Being small ($a_\mu = \hbar^2/m_\mu e^2 \approx 2.56 \cdot 10^{-11}$ cm is the Bohr radius of a muonic hydrogen atom, m_μ is the muon mass) and electrically neutral, muonic atoms of hydrogen isotopes easily penetrate through electron shells of neighbouring molecules and approach their nuclei as close as about a muon-atomic unit length a_μ. As a result, a series of atomic and molecular processes can occur:

- Elastic scattering of the muonic atoms by the nuclei of hydrogen isotopes.
- Transitions between hyperfine structure levels in muonic atoms.
- Muon transfer from light to heavy hydrogen isotopes (isotope exchange reactions).
- Formation of muonic molecules $pp\mu$, $pd\mu$, $dd\mu$, $dt\mu$, $tt\mu$ or $pt\mu$.
- Muon transfer from nuclei of hydrogen isotopes to nuclei of elements with charge $Z > 1$.

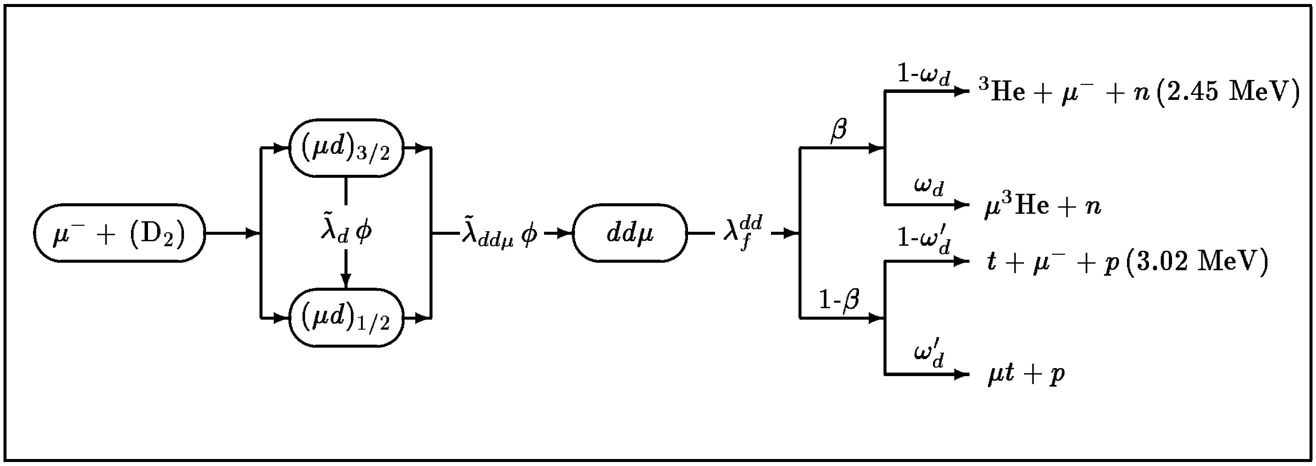

Figure 1: Kinetics of muonic reactions in pure deuterium. Explanation of the different rates is given below.

The distance between the nuclei of a muonic molecule being very small, fusion (muon catalyzed fusion or μCF) occurs. As a result, a muon can get free and induce a muon catalysis chain. Fig. 1 shows the kinetics of the reactions in a pure deuterium target, where $\tilde{\lambda}_{dd\mu}$ is the effective formation rate of the $dd\mu$ molecules, λ_f^{dd} is the nuclear fusion rate in $dd\mu$ molecules, $\tilde{\lambda}_d$ is the effective rate of the transition between hyperfine levels of the μd atom ($F = 3/2 \rightarrow F = 1/2$, F being the total spin of the atom), β is the relative probability for a neutron-yielding fusion reaction, ω_d and $\omega_d^{'}$ are the muon sticking coefficients to ^{3}He and tritium nuclei, respectively.

Processes yielding formation of muonic molecules and nuclear fusion of hydrogen isotopes have been intensively investigated, both theoretically and experimentally [1–4]. The experiments confirm the predicted resonant mechanism for $dd\mu$ and $dt\mu$ molecular formation.

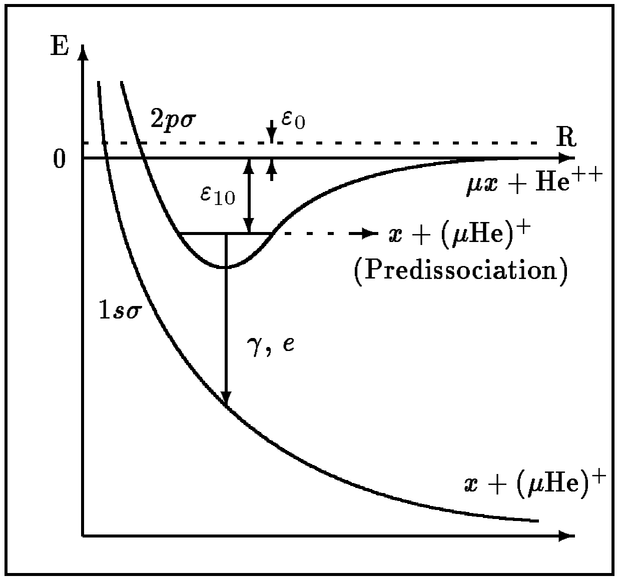

Figure 2: Scheme of the molecular charge exchange mechanism of muonic deuterium on helium nuclei. ε_0 is the collision energy between the muonic hydrogen atom and the helium nucleus, and ε_{10} is the binding energy of the muonic molecule in the state of angular momentum $J = 1$ and vibrational quantum number $\nu = 0$.

The study of processes yielding charge nonsymmetric muonic molecules like μxZ ($x \equiv p, d, t$ and $Z > 1$) and nuclear fusion started about fifteen years ago. Fig. 2 shows the molecular charge exchange mechanism of muonic hydrogen on helium nuclei, calculated by Aristov et al. [5] in 1981. One year later, a first measurement was performed and the suggested mechanism was observed [6]. When muonic hydrogen atoms μx are formed in a mixture of hydrogen and helium, muon transfer to helium nuclei occurs via formation of an intermediate μ-molecular complex μxHe in an excited state $2p\sigma$. The deexcitation occurs (see Fig. 3) either by a predissociation mechanism, where the molecule decays into a muonic helium atom and a hydrogen isotope nucleus with a rate λ_p, or pass into the molecular ground state $1s\sigma$ with emission of a γ (with a rate λ_γ) or an Auger electron (with a rate λ_e) and then decays into a hydrogen isotope nucleus x and a muonic atom of helium in the ground state $(\mu\text{He})_{1s}$. These processes were later confirmed in many measurements of muon transfer from μp, μd and μt atoms to helium isotopes [7–13]. Figs. 4 and 5 show the currently available experimental and theoretical values of rates λ^x_{He} for muon transfer from muonic hydrogen atoms in the ground state $(\mu x)_{1s}$ to helium

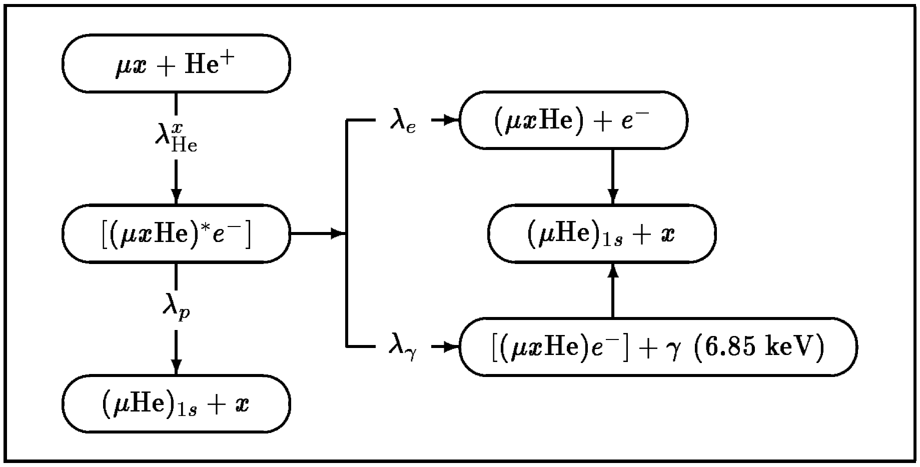

Figure 3: Muon transfer to helium predominantly proceeds via the formation of a μxHe molecule with rate $\lambda^x_{\rm He}$. Neglecting the nuclear fusion reaction, this molecule mainly disappears by predissociation with a rate λ_p or by deexcitation with rates λ_γ and λ_e.

isotopes nuclei.

Other muon transfer channels to helium exist (i.e. direct muon transfer to the ground state, radiative transfer and by electron conversion), but with substantially smaller (more than two orders of magnitude) rates compared to molecular charge exchange [5]. Therefore, the formation rate of μxHe molecules is called the muon transfer rate to helium. Partial probabilities for the different μxHe decay channels are calculated in Refs. [15–19]. The goal of this proposal being the study of $\mu d\,^3$He and $\mu d\,^4$He systems, Table 1 lists only the relevant quantities.

We do not consider the fusion reaction induced by other hydrogen isotopes because of the much lower formation rate of the μpHe molecules, and the inherent difficulties of dealing with tritium.

The Fig. 6 shows a scheme of atomic, molecular and nuclear processes occurring after the stop of negative muons in a mixture of $D_2 + {}^3$He. In addition to the mechanisms described previously by Fig. 1, nuclear fusion from charge nonsymmetric molecules may occur [21] via two different channels,

- emission of heavy charged particles with a rate λ_f^p,

$$\mu d\,^3\mathrm{He} \rightarrow \alpha + p\,(14.7\ \mathrm{MeV}) + \mu^- \qquad (1)$$

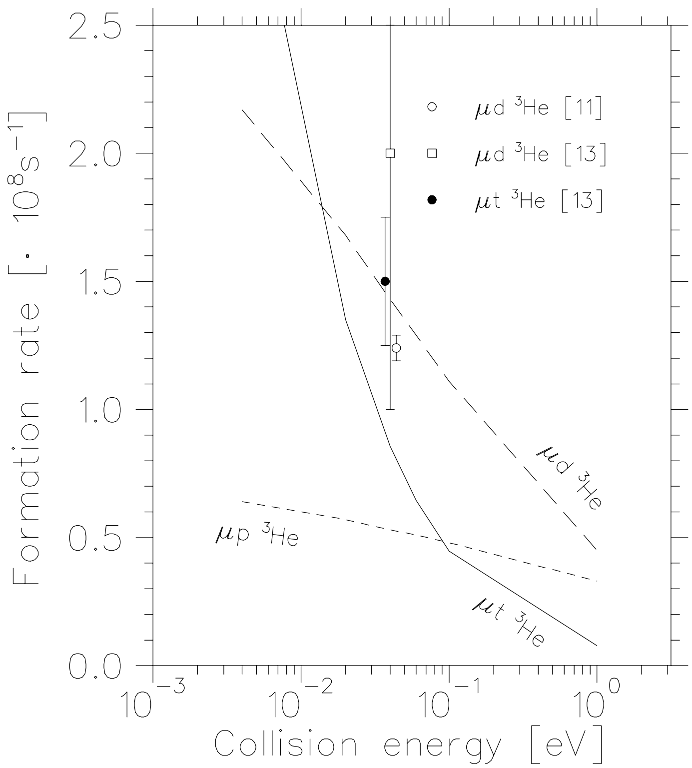

Figure 4: Rates of formation of muonic molecules $\mu x\,{}^3$He as function of collision energy. Curves represent the calculations of Ref. [14]. Theoretical and experimental values for $\mu t\,{}^3$He have been divided by a factor 10.

- emission of a hard γ quantum with a rate λ_f^Γ,

$$\mu d\,{}^3\mathrm{He} \rightarrow \mu^5\mathrm{Li} + \gamma\,(16.4\ \mathrm{MeV}) \tag{2}$$

The total fusion rate $\lambda_f^{d\,{}^3\mathrm{He}}$ is given by $\lambda_f^{d\,{}^3\mathrm{He}} = \lambda_f^p + \lambda_f^\Gamma$. The nuclear fusion in a $\mu d\,{}^4$He molecule can only process radiatively with a rate $\lambda_f^{d\,{}^4\mathrm{He}}$,

$$\mu d\,{}^4\mathrm{He} \rightarrow \mu^6\mathrm{Li} + \gamma\,(1.48\ \mathrm{MeV})\,. \tag{3}$$

As shown in Table 2, the theoretical estimates [17, 22–24] of the fusion rates in muonic hydrogen-helium molecules differ considerably from each other. According to the type of calculation, the fusion rate of the $\mu d\,{}^3$He molecules ranges over nine orders of magnitude. The pioneering measurement of Balin et al. [25] gives an upper limit of the fusion rate in the $\mu d\,{}^3$He system. No measurement has been performed yet about the nuclear fusion of $\mu d\,{}^4$He molecules.

In comparison with the resonant formation rate of $dt\mu$ molecules, $\lambda_{dt\mu} \sim 10^{10}\mathrm{s}^{-1}$ [26], and the associated fusion rate $\lambda_f = 10^{12}\mathrm{s}^{-1}$ [27], the rates of formation of nonsymmetric muonic molecules and nuclear fusion are very small.

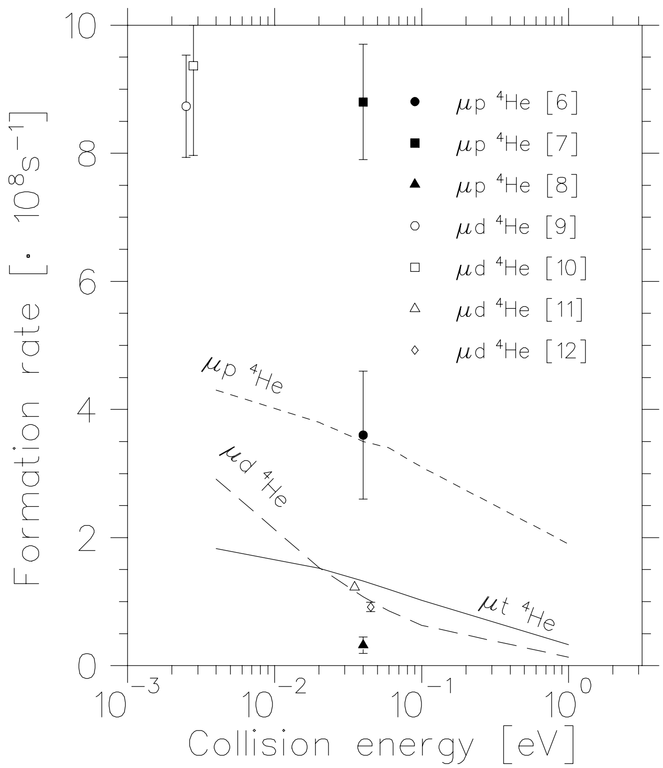

Figure 5: Rates of formation of muonic molecules $\mu x\,^4$He as function of the collision energy. Curves represent the calculations of Ref. [14]. Theoretical and experimental values for $\mu p\,^4$He have been multiplied by a factor 10, while those for $\mu d\,^4$He have been divided by 3.

However, their measurement may become a powerful tool for testing the calculation algorithm for the basic characteristics of the molecules. Eventually, this may nicely contribute to the understanding of the kinetics of cascade transitions in muonic atoms of hydrogen isotopes in mixtures of hydrogen isotopes and helium.

This study can also be of valuable help for other topics:

1. There is a considerable lack of information about nuclear interactions in the eV–keV energy region[1]. Such energies, however, are attainable in muonic systems. By lack of information, we mean not only the dynamics of nuclear transitions in this energy interval is not well understood, but also that the validity of the usual properties of the strong interactions is not guaranteed. Properties of strong interactions as charge symmetry,

[1] Our knowledge comes mainly from cold neutron-nuclei interactions, namely on the scattering lengths of nn, nd and nHe in different spin states.

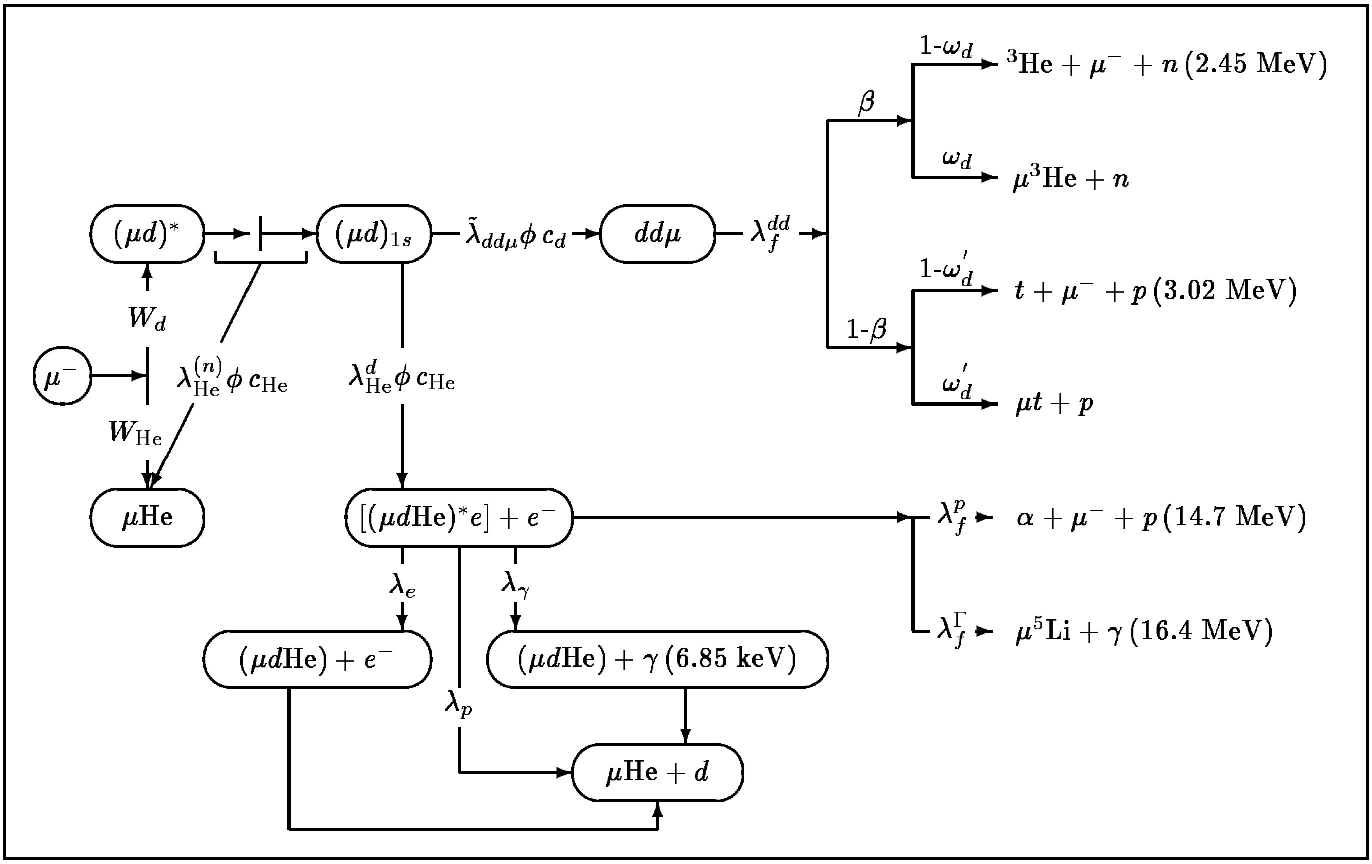

Figure 6: Atomic, molecular and nuclear processes occurring after muon stop in a D_2 + ^{3}He mixture. Rates and states are described in the text. To simplify the notation, the symbol He is used instead of ^{3}He.

iso-invariance, the character of P- and T- invariance (or its violation) are all established mainly in the MeV region and, up to now, have only been extrapolated to the low-energy region (citation from Ref. [28]).

2. The study of fusion reactions between light nuclei is important also for astrophysics. For example, in stars and in the Galaxy one finds the deficiency of light nuclei (except for ^{4}He) as compared with the predictions based on the theory of thermonuclear reactions and generally adapted models. Deuterium, for example, disintegrates in stars at T $\geq$ 50 eV, Li at T $\geq$ 200 eV, and so on. To explain this phenomenon modified star models are usually proposed, which assume that in the extrapolation of nuclear cross sections to the astrophysical energy region ($\sim$keV) no reso-

Table 1: Theoretical rates for predissociation (λ_p) and deexcitation of the molecules $\mu d\,^3$He and $\mu d\,^4$He with emission of a 6.85 keV γ-ray (λ_γ) or of a conversion electron (λ_e). *Values in italic mode* are calculated using $\lambda_\gamma = 1.55 \cdot 10^{11}\mathrm{s}^{-1}$ for ^{3}He and $\lambda_\gamma = 1.69 \cdot 10^{11}\mathrm{s}^{-1}$ for ^{4}He taken from Ref. [20].

Rate	$\mu d\,^3$He					$\mu d\,^4$He			
$[\cdot 10^{11}\mathrm{s}^{-1}]$	[15]	[16]	[17]	[18]	[19]	[15]	[16]	[17, 19]	[18]
λ_p	2.77	7.0	5.06	3.22	5.01	1.38	2.4	1.67	1.2
λ_γ	1.58			1.52		1.74			1.84
λ_e	0.41					0.43			
$\frac{\lambda_\gamma}{\lambda_\gamma+\lambda_p}$	0.363	*0.181*	*0.234*	0.325	*0.236*	0.558	*0.413*	*0.503*	0.605

Table 2: Estimated fusion reaction rates in $\mu d\,^3$He and $\mu d\,^4$He muonic deuterium-helium molecules. The experimental value is an upper limit of the fusion rate.

Rate	Theory			Experiment
$[\mathrm{s}^{-1}]$	[17]	[22]	[23]	[25]
$\lambda_f^{d\,^3\mathrm{He}}$	10^6	10^2	10^{11}	$\leq 4 \cdot 10^8$
$\lambda_f^{d\,^4\mathrm{He}}$			10^{11}	

nances or other anomalies of the cross sections occur. It is not excluded, however, that nuclear cross sections have a resonance character, which leads to intensive burning of the light elements in stars (citation from Ref. [29]).

The next sections will be dedicated to the presentation of the experimental technique aiming at measuring the processes of formation of muonic molecules $\mu d\,^3$He, $\mu d\,^4$He and their nuclear fusion reaction rates. A counting rates estimate of the quantities determined by the analysis of the experimental data will also be provided.

2. Description of the experiment

The measurement of the time distribution of the 6.85 keV γ-rays emitted by the deexcitation of the μdHe molecule will provide an essential information on the homogeneity and purity of the D_2+He mixture (which could be directly compared to some of the results of PSI experiment R–94–03 [30], presently under evaluation). The determination of the probability of radiative deexcitation will be used to normalize the yields of the fusion products (high energy gamma's and protons).

In order to optimize the muon stopping in the mixture (and consequently the counting rates), we first thought of using a mixture of deuterium–helium in the liquid phase. Unfortunately, it was found very difficult to measure the 14.7 MeV fusion protons, because of their short range in liquid deuterium (15 mm) compared to the target size. Therefore we decided to make the experiment in gas at low (30 K) temperature to take advantage of the high μdHe formation rate.

2.1 D_2+^{3}He mixture

The production rate of the $\mu d\,^3$He complex, and the partial rate of the fusion reaction Eqs. (1) and (2) can be efficiently measured with an atomic concentration of helium of $c_{^3\mathrm{He}} = 0.10$. Hence, the number of $\mu d\,^3$He complexes produced is

$$N_{\mu d\,^3\mathrm{He}} \;=\; N_\mu \,\frac{\lambda^d_{^3\mathrm{He}}\,\phi\, c_{^3\mathrm{He}}}{\lambda}\, q_{1s}\, W_d \tag{4}$$

and the number of those still existing at time t is (time $t = 0$ is defined as the time of arrival of the muon in the mixture, $\lambda_2 \gg \lambda$ and $t \gg \lambda_2^{-1}$)

$$N_{\mu d\,^3\mathrm{He}}(t) \;=\; N_\mu \,\frac{\lambda^d_{^3\mathrm{He}}\,\phi\, c_{^3\mathrm{He}}}{\lambda_2}\, q_{1s}\, W_d\; e^{-\lambda t} \tag{5}$$

with

$$\lambda \;=\; \lambda_0 \,+\, \lambda^d_{^3\mathrm{He}}\phi\, c_{^3\mathrm{He}} \,+\, \tilde{\lambda}_{dd\mu}\,\phi\,\beta\, c_d\, \omega_d \tag{6}$$

$$\lambda_2 \;=\; \lambda_f^{d\,^3\mathrm{He}} + \lambda_p + \lambda_\gamma + \lambda_e \tag{7}$$

where N_μ is the number of muon stops in the D_2+^{3}He mixture, λ_0 is the free muon decay rate, $\lambda^d_{^3\mathrm{He}}$ is the rate for muon transfer from μd atoms in the ground state to ^{3}He nuclei, λ_2 is the total disappearance rate of the molecule, $\phi = 0.075$ is the density of the D_2 + ^{3}He mixture relative to liquid hydrogen density ($N_0 = 4.25\cdot 10^{22}$ cm^{-3}), $c_{^3\mathrm{He}}$ is the atomic concentration of ^{3}He in the D_2+ ^{3}He mixture, $\tilde{\lambda}_{dd\mu}$ is the effective $dd\mu$ molecular formation rate corresponding to the chosen target temperature, β is the relative probability for a neutron-yielding fusion reaction in a $dd\mu$ molecule, ω_d is the probability for a muon to stick to a ^{3}He nucleus resulting from the fusion reaction in the $dd\mu$ molecule, $q_{1s} = 0.75$ is the probability for the μd atom formed in an excited state to reach the ground state [31, 32], $W_d = 0.84$, is the probability of having the muon initially captured by a deuterium atom ($W_d = (1 + A\, c_{\mathrm{He}}/(1 - c_{\mathrm{He}}))^{-1}$, where A is the relative muon atomic capture probability by He atom compared to deuterium ($A = 1.7 \pm 0.2$) [33]).

Measured yields and time distributions of γ and protons from the fusion reaction in a $\mu d\,^3$He molecule are defined as

$$N_\Gamma = N_{\mu d\,^3\mathrm{He}} \frac{\lambda_f^\Gamma}{\lambda_2} \varepsilon_\Gamma \qquad (8)$$

$$N_p = N_{\mu d\,^3\mathrm{He}} \frac{\lambda_f^p}{\lambda_2} \varepsilon_p \qquad (9)$$

$$\frac{dN_\Gamma}{dt}(t) = N_{\mu d\,^3\mathrm{He}}(t)\, \lambda_f^\Gamma\, \varepsilon_\Gamma = N_\mu\, \lambda_{^3\mathrm{He}}^d\, \phi\, c_{^3\mathrm{He}}\, q_{1s}\, W_d \frac{\lambda_f^\Gamma}{\lambda_2} \varepsilon_\Gamma\, e^{-\lambda t} \qquad (10)$$

$$\frac{dN_p}{dt}(t) = N_{\mu d\,^3\mathrm{He}}(t)\, \lambda_f^p\, \varepsilon_p = N_\mu\, \lambda_{^3\mathrm{He}}^d\, \phi\, c_{^3\mathrm{He}}\, q_{1s}\, W_d \frac{\lambda_f^p}{\lambda_2} \varepsilon_p\, e^{-\lambda t} \qquad (11)$$

with

$$\lambda_3 = \lambda_p + \lambda_\gamma + \lambda_e$$

$$\lambda_3 \gg \lambda_f^{d\,^3\mathrm{He}} \Rightarrow \lambda_2 \simeq \lambda_3 \qquad (12)$$

where $\lambda_f^{d\,^3\mathrm{He}}$, λ_3 are the total rates for nuclear fusion in a $\mu d\,^3$He molecule and for decay of $\mu d\,^3$He complex in $2p$ state, respectively; ε_Γ and ε_p are the detection efficiencies for fusion gammas and protons, respectively.

The yield and time distribution of the 6.85 keV radiation are defined as

$$N_\gamma = N_{\mu d\,^3\mathrm{He}} \frac{\lambda_\gamma}{\lambda_2} \varepsilon_\gamma \qquad (13)$$

$$\frac{dN_\gamma}{dt}(t) = N_{\mu d\,^3\mathrm{He}}(t)\, \lambda_\gamma\, \varepsilon_\gamma = N_\mu\, \lambda_{^3\mathrm{He}}^d\, \phi\, c_{^3\mathrm{He}}\, q_{1s}\, W_d \frac{\lambda_\gamma}{\lambda_2} \varepsilon_\gamma\, e^{-\lambda t} \qquad (14)$$

where ε_γ is the corresponding detection efficiency. Equations (10), (11) and (14) are valid if the conditions $\lambda_2 \gg \lambda$ and $t \gg \lambda_2^{-1}$ are fulfilled.

By analysing the time distributions of the deexcitation and fusion γ-rays and those of the fusion protons, λ is obtained and $\lambda_{^3\mathrm{He}}^d$ can be checked, using Eq. (6):

$$\lambda_{^3\mathrm{He}}^d = \frac{\lambda - \lambda_0 - \tilde{\lambda}_{dd\mu}\, \phi\, \beta\, c_d \omega_d}{\phi\, c_{^3\mathrm{He}}} \qquad (15)$$

with $\tilde{\lambda}_{dd\mu}, \beta, \omega_d$ being known from other experimental results [34, 35].

The relative deexcitation probability of the $[(\mu d^3\mathrm{He})e]$ molecule, a, via the radiative channel can be found from

$$a = \frac{\lambda_\gamma}{\lambda_2} \simeq \frac{\lambda_\gamma}{\lambda_3} = \frac{N_\gamma}{N_{\mu d\,^3\mathrm{He}}\, \varepsilon_\gamma} \qquad (16)$$

The partial rates of the radiative and protonic channels can be directly extracted from the number of recorded 16.4 MeV γ-rays and 14.7 MeV protons:

$$\lambda_f^\Gamma = \frac{N_\Gamma \, \lambda_2}{N_{\mu d^3\mathrm{He}} \, \varepsilon_\Gamma} \tag{17}$$

$$\lambda_f^p = \frac{N_p \, \lambda_2}{N_{\mu d^3\mathrm{He}} \, \varepsilon_p} \tag{18}$$

$$\frac{\lambda_f^\Gamma}{\lambda_f^p} = \frac{N_\Gamma \, \varepsilon_p}{N_p \, \varepsilon_\Gamma} \tag{19}$$

where the value of λ_2 is derived from Refs. [15–19]. If the fusion rate is found so small that the number of fusion products does not exceed the background level, one can determine an upper limit of the partial rate for the fusion reaction in a muonic μd^3He molecule from Eqs. (8), (9) and (12):

$$\lambda_f^\Gamma = \frac{\lambda_3}{N_{\mu d^3\mathrm{He}} \, \varepsilon_\Gamma}$$

$$\lambda_f^p = \frac{\lambda_3}{N_{\mu d^3\mathrm{He}} \, \varepsilon_p} \tag{20}$$

It is also important to remark that the branching ratio $\lambda_f^\Gamma/\lambda_f^p$ was found to be of the order of 10^{-4} by studying the reaction ^{2}H(^{3}He,γ)^{5}Li at collision energies of a few 10 keV [36]. A rough extrapolation of this ratio to the keV-energy region indicates that the main information about the μd^3He reaction will most certainly be provided by the proton data.

2.2 D_2+^{4}He mixture

According to the higher molecular formation rate compared to ^{3}He, one can select a smaller atomic concentration of ^{4}He, namely $c_{^4\mathrm{He}} = 0.03$. Consequently, the probability for the μd to reach the ground state becomes $q_{1s} = 0.90$ and the capture probability by a deuterium atom is $W_d = 0.95$. Otherwise, the data evaluation differs from that of ^{3}He only by the fact that there is only one kind of fusion reaction which is described by Eq. (3).

2.3 Experimental Setup

The experimental apparatus is schematically shown in Fig. 7. This includes a cryogenic deuterium target, detectors for muons and muon decay electrons, Si detectors to record charged products (protons), Ge and BGO detectors to record the 6.85 keV and fusion γ-rays from reactions (2) and (3). A NE213

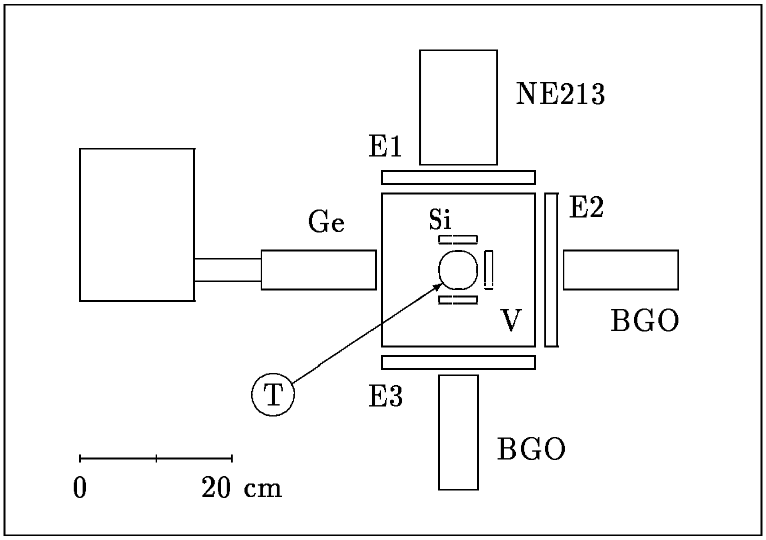

Figure 7: Conceptual view of the experimental setup viewed towards the beam direction. T — target, V — vacuum chamber, E1, E2, E3 — electron counters, Ge — germanium detector, NE213 — neutron detector, BGO — detectors of hard γ-quanta. Small dashed boxes around the target represent Si detectors for protons detection.

neutron detector will monitor the different measurements, using the time distribution and yields of the neutron emitted after *dd*-fusion.

The experiment should be carried out in the μE4 muon channel at PSI. The muon beam intensity at the target entrance window for an average momentum of $P_\mu = 37$ MeV/c is $I_\mu \simeq 2 \cdot 10^4$ s^{-1} (chromatic mode, for a proton beam of 1 mA on target E). The experiment involves measurements with $D_2 + {}^3He$, $D_2 + {}^4He$ mixtures and a background measurement with pure deuterium (see Table 3).

Table 3: Experimental conditions.

Target	c_{He} [%]	Temperature [K]	Time [hours]
$D_2 + {}^3He$	10	30	200
$D_2 + {}^4He$	3	30	200
D_2		30	100

In the on-line mode, information on an event is recorded if there is a signal of a muon stop in the target volume and

- a signal from the muon decay electron counters within the resolution time of 5 μs starting from the moment of the muon stop, and

- a signal from at least one of the detectors (Ge, Si, NE213 or BGO) within the resolution time.

Provided the first two criteria are fulfilled, time distributions of recorded muon decay electrons are also measured.

In the off-line mode, recorded events are analysed only if at least one of the criteria $t_i < t_e$ is fulfilled (t_i are the times of detection provided by the Ge, Si, BGO and NE213 detectors, t_e that from the electron counters). Note that the time distribution of muon decay electrons against the moment of appearance of a γ-quantum from the fusion reaction in the μdHe molecule, or a 6.85 keV muonic γ-ray radiation, is described with a rate λ_0.

According to Eq. (4), and requiring a systematic coincidence with a signal from one of the decay electron counters, the resulting number of μdHe molecules will be defined as

$$N^e_{\mu d\mathrm{He}} = N_\mu \frac{\lambda^d_{\mathrm{He}}\, \phi\, c_{\mathrm{He}}}{\lambda}\, \varepsilon_e\, q_{1s}\, W_d = N_e^{\mathrm{reg}} \frac{\lambda^d_{\mathrm{He}}\, \phi\, c_{\mathrm{He}}}{\lambda}\, q_{1s}\, W_d \qquad (21)$$

where ε_e is the electron counters efficiency, N_e^{reg} is the number of muon decay electrons recorded, c_{He} and λ^d_{He} are used for ^{3}He and ^{4}He. The quantities λ^d_{He} and λ are obtained by fitting the 6.85 keV muonic γ-ray time distributions, using Eq. (15).

3. Estimates of rates

At the muon beam momentum $P_\mu = 37$ MeV/c the intensity of muon stops in the volume of gas deuterium target is $2\cdot 10^4$ s^{-1}. The electronics is protected from beam pileup within a $\pm 5\,\mu$s time gate and causes a reduction of the effective beam of 18%. These estimates of the relative probabilities for radiative deexcitation of $\mu d\,^3$He and $\mu d\,^4$He molecules and of the rates for nuclear fusion reactions in them are derived with the following values:

$\lambda^d_{^3\mathrm{He}}(30\,\mathrm{K}) =$	$2.2 \cdot 10^8\,\mathrm{s}^{-1}$	theoretical rates
$\lambda^d_{^4\mathrm{He}}(30\,\mathrm{K}) =$	$8.7 \cdot 10^8\,\mathrm{s}^{-1}$	from Ref. [14]
$\lambda_3(\mu d\,^3\mathrm{He}) =$	$6 \cdot 10^{11}\,\mathrm{s}^{-1}$,	
$\lambda_3(\mu d\,^4\mathrm{He}) =$	$3.5 \cdot 10^{11}\,\mathrm{s}^{-1}$	average over Refs. [15–19]

$$
\begin{aligned}
\lambda_\gamma/\lambda_3(\mu d\,{}^3\mathrm{He}) &= 0.28, \\
\lambda_\gamma/\lambda_3(\mu d\,{}^4\mathrm{He}) &= 0.5 \qquad \text{average over Refs. [15–19]}
\end{aligned}
$$

$$
\begin{aligned}
\tilde{\lambda}_{dd\mu} &= 0.04 \cdot 10^6\,\mathrm{s}^{-1} \quad [35] \\
\omega_d &= 0.122 \quad [34] \\
\beta &= 0.58 \quad [34]
\end{aligned}
$$

$$
\begin{aligned}
\varepsilon_\Gamma(16.4\,\mathrm{MeV}) &= 5.4 \cdot 10^{-3} \\
\varepsilon_\Gamma(1.5\,\mathrm{MeV}) &= 1.5 \cdot 10^{-2}
\end{aligned}
$$

$$
\begin{aligned}
\varepsilon_\gamma &= 4.4 \cdot 10^{-3} \\
\varepsilon_p &= 0.20 \\
\varepsilon_e &= 0.32
\end{aligned}
$$

Each of the data taking with deuterium-helium mixtures being 200 hours long, the following results can be expected. The number of recorded 6.85 keV muonic γ-rays, N_γ^e, and the number of $[(\mu d\,{}^3\mathrm{He})e]$ and $[(\mu d\,{}^4\mathrm{He})e]$ molecules, $N^e_{\mu d\mathrm{He}}$, formed (both requiring a decay electron coincidence) are:

$\underline{\mu d\,{}^3\mathrm{He}}$

$$
N^e_{\mu d\,{}^3\mathrm{He}} = N_\mu \frac{\lambda^d_{{}^3\mathrm{He}}\,\phi\, c_{{}^3\mathrm{He}}}{\lambda}\, q_{1s}\, W_d\, \varepsilon_e = 1.9 \cdot 10^9 \qquad (22)
$$

$$
N^e_\gamma = N^e_{\mu d\,{}^3\mathrm{He}} \frac{\lambda_\gamma}{\lambda_3}\, \varepsilon_\gamma = 2.3 \cdot 10^6 \qquad (23)
$$

$\underline{\mu d\,{}^4\mathrm{He}}$

$$
N^e_{\mu d\,{}^4\mathrm{He}} = N_\mu \frac{\lambda^d_{{}^4\mathrm{He}}\,\phi\, c_{{}^4\mathrm{He}}}{\lambda}\, q_{1s}\, W_d\, \varepsilon_e = 2.6 \cdot 10^9 \qquad (24)
$$

$$
N^e_\gamma = N^e_{\mu d\,{}^4\mathrm{He}} \frac{\lambda_\gamma}{\lambda_3}\, \varepsilon_\gamma = 5.8 \cdot 10^6 \qquad (25)
$$

With such statistics, the uncertainty on the experimental rates $\lambda^d_{{}^3\mathrm{He}}$ and $\lambda^d_{{}^4\mathrm{He}}$ will mainly depend on the precision of the ^{3}He and ^{4}He concentrations in the deuterium-helium mixtures, which are typically of $\pm 3\%$.

The accuracy of the measured ratio λ_γ/λ_3 depends on the uncertainty of the helium concentration and on the precision of the knowledge of the 6.85 keV γ-ray detection efficiency. For the measurements with $D_2 + {}^3\mathrm{He}$ and $D_2 + {}^4\mathrm{He}$ mixtures, we estimate the uncertainty in the ratio λ_γ/λ_3 to be about 10%.

The upper limit estimates of the nuclear fusion rates in the $\mu d\,^3$He and $\mu d\,^4$He molecules are:

<u>$\mu d\,^3$He</u>

$$\lambda_f^\Gamma = \frac{\lambda_3}{N^e_{\mu d\,^3\mathrm{He}}\,\varepsilon_\Gamma} = 5.9 \cdot 10^4\,\mathrm{s}^{-1} \tag{26}$$

$$\lambda_f^p = \frac{\lambda_3}{N^e_{\mu d\,^3\mathrm{He}}\,\varepsilon_p} = 1.6 \cdot 10^3\,\mathrm{s}^{-1} \tag{27}$$

<u>$\mu d\,^4$He</u>

$$\lambda_f^\Gamma = \frac{\lambda_3}{N^e_{\mu d\,^4\mathrm{He}}\,\varepsilon_\Gamma} = 8.9 \cdot 10^3\,\mathrm{s}^{-1} \tag{28}$$

These measurements aim at determining the total and partial nuclear fusion rates in $\mu d\,^3$He and $\mu d\,^4$He molecules.

4. Readiness

The target will be built at JINR (Dubna). The assembly of the vacuum and cryogenic systems, and the final tests should be done at PSI a few weeks before the measurement period.

The detectors will be provided by the institutions involved in this collaboration.

The data acquisition system will be the same as the one used for previous μCF experiments [30].

We should be ready by August 1996.

5. Beam Time Required

The experiment should be carried out in the μE4 muon channel. Taking into account some time for setup, calibrations and beam intensity fluctuation, a 4-weeks period should be sufficient for the measurements we present here.

6. Safety

No dangerous radioactivity is involved in this experiment. Only some calibration sources will be used.

The critical parts of the target cell are the thin windows in direction to the silicon detectors. They will be thoroughly tested before they are used during the experiment. The usual hydrogen safety precautions will be taken.

No extraordinary precautions should be necessary.

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