Determination of Muonic Helium X-Ray Yields after Muon-Catalyzed *pd*, *dd*, and *dt* Fusion

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X-ray yields of the muonic helium (2-1) transition from μ-catalyzed fusion have been measured for the first time in various mixtures of hydrogen isotopes. They were determined to be 0.032(4), 0.016(2), and 0.0019(5) for *pd*, *dd*, and *dt* fusion, respectively.

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Negative muons in a mixture of hydrogen isotopes give rise to various kinds of muon-catalyzed fusion (MCF) reactions.[1] After a fusion process either the muon is released, thus being able to serve as a catalyst for further fusion, or it is bound in an atomic orbital of principal quantum number n and angular momentum quantum number l ("sticking"). The main reactions with sticking are (n denoting a neutron)

$$p\mu d \rightarrow (\mu\,^3\mathrm{He})_{nl}+\gamma, \quad Q_{1s}=5.502\ \mathrm{MeV}, \tag{1}$$

$$d\mu d \rightarrow (\mu\,^3\mathrm{He})_{nl}+n, \quad Q_{1s}=3.277\ \mathrm{MeV}, \tag{2}$$

$$d\mu t \rightarrow (\mu\,^4\mathrm{He})_{nl}+n, \quad Q_{1s}=17.598\ \mathrm{MeV}. \tag{3}$$

Because of the recoil of the μHe the muon may be stripped off by ionization or transfer while the μHe is moving through matter. These "reactivation" processes reduce the sticking value from the initial value ("primary sticking") to a final value ("final sticking") to which most experiments are sensitive. Muons in excited levels of the μHe may deexcite under x-ray emission. The x-ray spectrum depends not only on the initial sticking in the atomic levels and the reactivation of the muon but also on intra-atomic transitions due to inelastic collisions, internal and external Auger effect, and Stark mixing. The first x-ray experiment was performed by Bossy *et al.*[2] and Angerer *et al.*,[3] the second by Nagamine *et al.*[4] Apart from preliminary communications,[3-5] so far only experimental intensity ratios of μHe transitions have been published for the *pd*- and *dd*-fusion reactions.[6] The first number given for the *dt*-fusion x-ray yield is in Ref. 3. Detailed calculations on reactivation and x-ray yields may be found in the works of Takahashi[7] and Cohen.[8]

The *dt*-fusion cycle is the cycle most intensively investigated during the last years.[3-5,7-10] From the time distribution of fusion neutrons, final-sticking values could be determined. The most recent experimental values[10] for final sticking are in fair agreement with a recent calculation,[8] but there is a clear discrepancy with a reported strong dependence of sticking on density and tritium concentration.[9] The measurement of muonic x rays provides an independent method to test our knowledge about sticking and reactivation.

The experiments were performed at SIN. The experi-

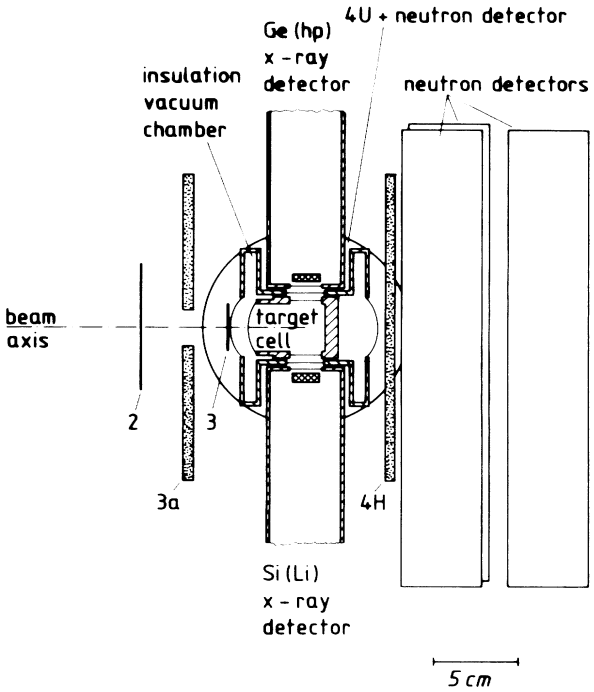

FIG. 1. Top view of the experimental setup for the *dt* experiment. Muons were detected with counters 2 and 3, electrons with counters 3a, 4U, 4H, and (not in the drawing) 4R and 4L.

mental setup for the *pd* and *dd* measurements[6] and the tritium apparatus[11] were already described. A description of the *dt* experiment (Fig. 1) will be given in the following. The target cell (inner diameter, 30 mm; length, 52 mm) was made of pure iron and coated with silver. Two Be windows allowed the x rays to leave the cell. A Ge (high purity) and a Si(Li) detector with active areas of 2 cm^2 and thicknesses of 1 and 0.5 cm, respectively, were used for radiation detection. The in-beam resolution was 420 eV FWHM at 8.2 keV for both detectors. Three plastic scintillation counters (NE201, $5\times5\times30$ cm^3) and a liquid scintillation counter (NE213, diameter 12.7 cm and thickness 10.2 cm) were placed behind and below the target cell to measure fusion neutrons. Plastic scintillation counters (NE102A) detected incoming muons and decay electrons. Data were recorded on tape with as few as possible hardware restrictions, so that time windows and thresholds could be set during the data analysis. A survey of the runs is given in Table I.

The measurement of μHe x rays from *dt* fusion, Eq. (3), required a coincidence with the fusion neutron firstly to suppress x rays from the *dd* reaction, Eq. (2), and secondly to reduce the huge bremsstrahlung background from tritium β decay; *dd*-fusion neutrons can easily be discriminated against by appropriate threshold setting. Moreover, the coincidence with a neutron emitted at about 90° relative to the x ray reduces strongly the Doppler broadening, an almost insurmountable obstacle in the case of a no-coincidence experiment with poor statistics. Figure 2(a) shows an x-ray spectrum coincident with *dt*-fusion neutrons in a 30-ns coincidence time window. The $\mu\,^4$He(2-1) line is clearly visible. If $I_{xn}(2\text{-}1)$ is the measured μHe(2-1) intensity in coincidence with a fusion neutron, the (2-1) x-ray yield $Y(2\text{-}1)$ per fusion is given by

$$Y(2\text{-}1)=I_{xn}(2\text{-}1)/(I_n\epsilon_x\eta_x), \tag{4}$$

where I_n is the intensity of fusion neutrons measured under the same conditions, ϵ_x the x-ray detector efficiency, and η_x the live-time correction of the detector electronics.

In liquids of pure deuterium and protium-deuterium mixtures, sufficient background reduction for x-ray spectra was achieved with the requirement of a delayed electron coincidence.[6] For these spectrum $Y(2\text{-}1)$ is given by a formula analogous to Eq. (4). The fusion probabilities Y_f per muon could be determined with the help of the neutrons and the 5.5-MeV γ rays, respectively, with the use of calculated neutron efficiencies and measured γ efficiencies. In the case of run 3, the probability of *dd* fusion was measured to be 0.098(9) compared with a calculated value of 0.101 when rates from the work of Nägele[12] are used for the *dd*-fusion cycle. For the runs 1 and 2, Y_f was determined to be 0.17(2) and 0.18(2), respectively, compared with theoretical values of 0.151 and 0.161, respectively, resulting from calculations similar to those of Bertl *et al.*[13] More details can be found in the work of Bossy.[14]

TABLE I. Survey of the performed muon-catalyzed fusion (MCF) measurements.

Run number	MCF reaction	Mixture[a]	Measuring time (h)
1	*pd*	H+0.66(4)% D	18.2
2	*pd*	H+5.7(3)% D	10.9
3	*dd*	Pure D	56.1
4	*dt* + *dd*	D+0.04% T	165.2
5	*dt* + *dd*	D+0.02% T	62.6

[a]All measurements with liquid targets, mixtures equilibrated; H=protium, D=deuterium, T=tritium.

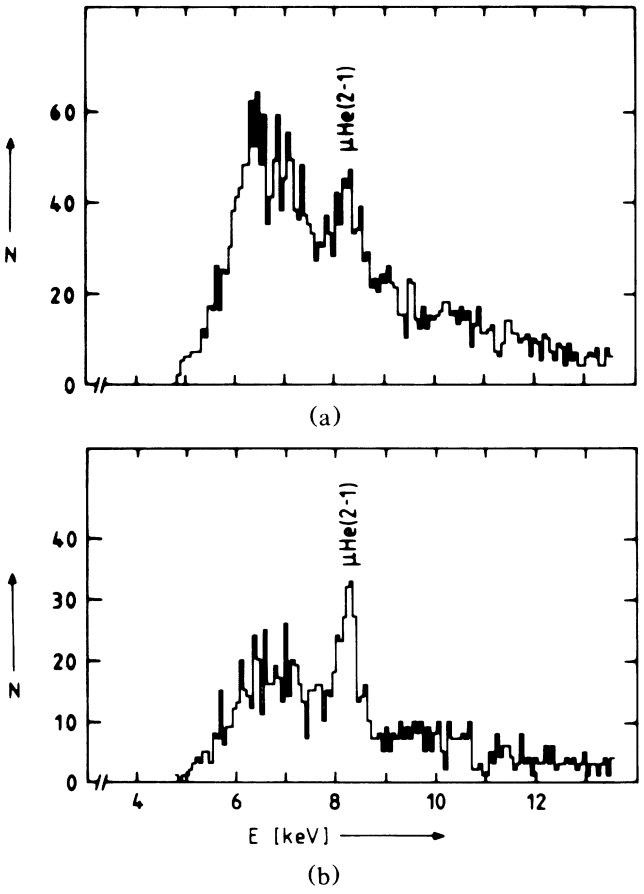

FIG. 2. X-ray spectra from the 0.04% tritium mixture (run 4) in coincidence with a delayed electron: (a) in a time window from 0.045 to 7 μs after the muon has been stopped in the target and with the additional coincidence of a fusion neutron (high threshold, *dt* neutrons only); (b) in a time window from 0 to 80 ns after the muon has been stopped in the target and with the additional coincidence of a fusion neutron (low threshold, *dd* and *dt* neutrons, but mostly *dd*).

The *dd* x-ray yield, measured in pure deuterium (run 3), could be checked with the *dt* measurements thanks to the fact that immediately after the μ stops, most of the fusion neutrons stem from *dd* reactions; the contribution of *dd* neutrons in the first 80 ns is 78% for the 0.04% tritium mixture.[15] This is due to the high $d\mu d$ molecular formation rate from the upper hyperfine (hf) state of the μd atom,[16,17] which is much faster than the transfer of the muon to the triton that determines the *dt*-cycle rate at low tritium concentrations. The dominance of *dd* fusion disappears as the upper hf level decays into the lower hf state, with a mean lifetime of about 30 ns, where the molecular formation rate is 70 times lower.[12] Figure 2(b) shows an x-ray spectrum in the first 80 ns after the muon has been stopped in the target in coincidence with mostly *dd* neutrons, i.e., a pulse-height setting well below 2.5 MeV; the time window was here broadened to 70 ns.

The experimental quantum yields were corrected as follows: X-ray intensities that were measured in coincidence with fusion neutrons comprised a contribution from *dd*-fusion radiation, because of the (small) probability that after a *dt* (or also a *dd*) neutron has opened the coincidence time window, a released muon can catalyze a *dd*-fusion reaction with x-ray emission. The concerned measurements were corrected with the x-ray yield from the pure-deuterium experiment. The correction was small: 12% for the *dt* yield and 2.5% for the *dd* yield of run 4.

Because of the small x-ray intensity in the case of *dt* fusion, special attention was paid to an effect that could have faked fusion x rays: μ transfer from hydrogen to helium. During the run time the estimated ^{3}He concentration, built up by the tritium decay, varied from 0.55 to 1.05 ppm. No increase of the μHe x-ray intensity with increasing age of the mixture was observed, which means that transfer processes to ^{3}He were not detectable. In run 4 the energies of the $\mu\,^4$He and $\mu\,^3$He (2-1) transitions were found to be 8.31(7) and 8.22(3) keV, respectively, which may be compared with calculated values of 8.222 and 8.148 keV, respectively. If we use the calculated transfer rate[18] and allow all muons to emit a (2-1) x-ray quantum (which is by far too high), the (2-1) yield is estimated a factor of 70 too low to account for the observed intensity. The measured $\mu\,^3$He energies from *dd* and *pd* fusion were also in good agreement with the expected values.

In Table II the x-ray yields from runs 1 through 4 are summarized and compared with calculations.[7,8] Included are also the x-ray intensity ratios from Ref. 6, which were partly updated after a refined data analysis. X-ray yields from run 5 were consistent with the results from run 4. The *pd*-fusion x-ray yields from runs 1 and 2 were 0.037(6) and 0.029(5), which average to the value quoted in Table II.

Recent calculations of x-ray yields by Cohen[8] are in fair agreement with the experimental results for *dt* and *dd* fusion. Takahashi's values,[7] however, agree only for *pd* fusion, where slowing-down effects on x-ray intensities play a minor role. With the exception of the μHe(4-1)/μHe(2-1) ratio in the case of *pd* fusion, and the μHe(3-1)/μHe(2-1) ratio in the case of *dt* fusion, the two theoretical x-ray intensity ratios[7,8] are in fair agreement with experiment.

The discrepancies of the most recent theoretical calculations[8] with experimental x-ray measurements are not dramatic. So current theories on sticking in muon-catalyzed fusion and the influence of μHe slowing down on x-ray intensities are basically confirmed by this experiment. The slightly lower experimental values may indi-

TABLE II. X-ray yield of the μH(2-1) line and intensity ratios of higher muonic helium transitions for muon-catalyzed *pd*, *dd*, and *dt* fusion.

	(2-1) x-ray yield Y(2-1)	Intensity ratios μHe(3-1)/μHe(2-1)	μHe(4-1)/μHe(2-1)
pd fusion			
Experiment (runs 1,2)	0.032(4)	0.052(5)	0.001(3)
Theory[a]	0.0310	0.0553	0.0161
dd fusion			
Experiment (run 3)	0.016(2)	0.13(2)	0.023(13)
Experiment (run 4)	0.018(4)	Not determined	Not determined
Theory[a]	0.0372	0.132	0.0188
Theory[b]	0.022(2)	0.11(2)	0.015(3)
dt fusion			
Experiment (run 4)	0.0019(5)	≤ 0.08[c]	0.20(13)
Theory[a]	0.0036	0.128	0.0189
Theory[b]	0.0024(4)	0.12	0.019

[a]Reference 7.
[b]Reference 8.
[c]95% confidence level.

cate either that the initial sticking is lower than calculated or that the enhancement of the (2-1) yield by the slowing-down process is overestimated. Starting from a calculated final-sticking value of $\omega=0.0054$ and a calculated yield of the (2-1) line in μ^4He of $Y(2\text{-}1)=0.0024$ as given by Cohen,[8] we scale his ω by the experimental- to theoretical-yield ratio

$$Y(2\text{-}1)_{\text{expt}}/Y(2\text{-}1)_{\text{theor}}=0.0019/0.0024$$

and obtain our final-sticking value of $\omega=0.0042(14)$, in excellent agreement with the recent mean value of Breunlich *et al.*,[10] $\omega=0.0045(5)$, based on a complete-cycle analysis.

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