Muon catalysis of p-Z fusion reactions at $Z > 1$

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The rate of the nuclear fusion reaction in the asymmetric molecule $Zp\mu$ ($Z > 1$) is low in comparison with the rate of the dissociation of the molecule and the decay of the muon.

The most important consequence of the formation of $dd\mu$ and $dt\mu$ molecules is the catalysis of nuclear fusion reactions.[1] The high rates of the reaction leading to the formation of the $dt\mu$ molecule, $\lambda_{dt\mu} \sim 10^8$ s^{-1}, and of the fusion reaction, $\lambda^f_{dt} \sim 10^{12}$ s^{-1}, in combination with the low attachment coefficient,[1,2] $\omega_s \sim 0.01$, suggests that muon catalysis in the dt system might be used for energy production.[3]

At first glance, it might appear promising to use muon-catalysis fusion reactions involving nuclei with $Z > 1$. For example, fusion reactions in the systems[4]

$$d + {}^3\text{He} \rightarrow \alpha + p + 18.3\ \text{MeV},$$

$$d + {}^6\text{Li} \rightarrow 2\alpha + 22.4\ \text{MeV},$$

are under consideration in connection with muon catalysis, and muon catalysis in the system[4,5]

$$p + {}^{11}\text{B} \rightarrow 3\alpha + 8.7\ \text{MeV}.$$

is also being discussed. These reactions are attractive because, for example, there are no neutrons in the final state. However, if muon catalysis is to be achieved, the $Zp\mu$ muonic molecule must be able to form.

TABLE I. Formation rates of He$p\mu$ and Li$p\mu$ muonic molecules calculated for $\epsilon_0 \sim 0.04$ eV

λ_m, 10^8 s^{-1}					
^{3}He$p\mu$	^{4}He$p\mu$	^{3}He$d\mu$	^{4}He$d\mu$	^{3}He$t\mu$	^{4}He$t\mu$
0.87	0.44	1.48	2.03	5.62	1.98

λ_m, 10^6 s^{-1}					
^{6}Li$p\mu$	^{7}Li$p\mu$	^{6}Li$d\mu$	^{7}Li$d\mu$	^{6}Li$t\mu$	^{7}Li$t\mu$
22.1	10.8	3.45	1.85	2.08	0.81

The formation of asymmetric ($Z > 1$) muonic molecules was discussed in Refs. 6–8 for the He$p\mu$ and Li$p\mu$ systems (for arbitrary isotopic mixtures). The bound states of the molecules were found, and their formation rates λ_m were calculated. These rates are listed in Table I for thermal collision energies, $\epsilon_0 \simeq 0.04$ eV. The calculated values of λ_m agree with the experimental data obtained for the muonic molecules ^{4}He$p\mu$ (Ref. 9), ^{4}He$d\mu$ (Ref. 10), ^{3}He$d\mu$, and ^{3}He$t\mu$ (Ref. 2).

On the other hand, the asymmetric $Zp\mu$ molecules are distinguished from the muonic molecules of hydrogen isotopes in that they form in an excited state, according to the classification of molecular terms, and they correspond to quasistationary states which dissociate by radiative or Auger transitions to a state of the continuum in the reaction

$$p\mu + Z \rightarrow Zp\mu \rightarrow Z\mu + p, \qquad (1)$$

which simulates direct charge exchange. According to the calculations of Refs. 7 and 8, the lifetime of the muonic molecules is on the order of 10^{-12} s.

Estimates of the rates of the fusion reactions of the nuclei in muonic molecules yield

$$\lambda^f \sim \begin{cases} 100 \text{ s}^{-1} \text{ for } {}^3\text{He}d\mu \\ 0.01 \text{ s}^{-1} \text{ for } {}^6\text{Li}d\mu \end{cases} \qquad (2)$$

The low rates of the fusion reactions in these molecules in comparison with those in muonic molecules of hydrogen stem primarily from the large equilibrium nuclear separation R_m, which is $\sim 4a_\mu$ for the He$p\mu$ molecule (a_μ is the first Bohr radius of muonic hydrogen) and $\simeq 6a_\mu$ for the Li$p\mu$ molecule (by way of comparison, we have $R_m \simeq 2a_\mu$ for muonic hydrogen molecules). As for the B$p\mu$ system, we note that the increase in the Coulomb barrier causes the equilibrium nuclear separation to reach[11]

$R_m \simeq 15a_\mu$, and even in the presence of bound states of the $^{11}\mathrm{B}p\mu$ molecule the rate of the fusion reaction, λ^f, is negligible not only in comparison with the dissociation rate of the molecule but also in comparison with the decay rate of the muon, $\lambda_0 \simeq 0.45 \times 10^6$ s^{-1}. We would expect that the direct charge exchange would be predominant at[12,13] $Z \geqslant 4$.

We thus see that in practice the comparatively large dimensions of the $Zp\mu$ molecules and their short lifetimes (combined with the high rate of direct charge exchange at $Z \geqslant 4$) make the fusion of p and Z nuclei in muonic molecules formed at $\epsilon \sim \epsilon_0$ unfeasible. As for the "in-flight" fusion reaction, we note that Bogdanova *et al.*[14] have shown that for the *dt* system this reaction would be strongly suppressed in comparison with the rate of fusion from a muonic-molecule state. Similar arguments apply to the $Zp\mu$ system. At the same time, with a significant increase in the temperature the rapid ionization of the target would rule out the formation of muonic molecules.[1]

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