AIP Proceedings

Possible influence of vacuum polarization on Q 1s in muon catalyzed DT fusion

B. Müller, J. Rafelski, M. Jändel, and S. E. Jones

Citation: AIP Conference Proceedings **181**, 105 (1988); doi: 10.1063/1.37909
View online: http://dx.doi.org/10.1063/1.37909
View Table of Contents:
http://scitation.aip.org/content/aip/proceeding/aipcp/181?ver=pdfcov
Published by the AIP Publishing

Articles you may be interested in

Boundaryvalue approach to nuclear effects in muoncatalyzed DT fusion
AIP Conf. Proc. **181**, 344 (1988); 10.1063/1.37920

Effect of nuclear interaction on muon sticking to helium in muon catalyzed dt fusion
AIP Conf. Proc. **181**, 330 (1988); 10.1063/1.37919

Muon losses in deuteriumtritium muoncatalyzed fusion due to fast transfer reactions to helium nuclei
AIP Conf. Proc. **181**, 161 (1988); 10.1063/1.37913

Investigation of Q 1s
AIP Conf. Proc. **181**, 57 (1988); 10.1063/1.37889

Density dependent stopping power and muon sticking in muon catalyzed DT fusion
AIP Conf. Proc. **181**, 355 (1988); 10.1063/1.37876

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 128.187.97.22 On: Tue, 01 Apr 2014 21:12:21

POSSIBLE INFLUENCE OF VACUUM POLARIZATION ON Q_{1s} IN MUON CATALYZED D-T FUSION

B. Müller[1,2] and J. Rafelski[1]
[1]Dept. of Physics, University of Arizona, Tucson, AZ 85721
[2]Inst. f. Theor. Physik, Universität, D-6000 Frankfurt, West Germany

M. Jändel
AFI, Roslagsvägen 100, S-10405 Stockholm, Sweden

S.E. Jones
Dept. of Physics, Brigham Young University, Provo, UT 84602

ABSTRACT

The vacuum polarization splitting of the M-shell states in muonic hydrogen can have a profound influence on the muonic de-excitation cascade in deuterium and tritium targets. The cascade also shows sensitive dependence on the precise rate of transfer processes between certain excited muonic deuterium and tritium atoms. Recent experimental data, where a much greater population of the $(d\mu)$ 1s state (q_{1s}) was found than previously predicted, can be explained if the transfer rates from the $(d\mu)$ M-shell are assumed to be strongly suppressed.

INTRODUCTION

Understanding of the atomic capture and de-excitation cascade of muons is of profound importance in the study of muon catalyzed fusion [1], because the fraction of muons reaching the deuterium ground state has a large influence on the overall fusion rate. In particular, the fusion cycle is inhibited by the slow transfer of muons between the ground states of deuterium and tritium. The muonic cascade is determined by a competition between radiative transitions, density dependent external Auger transitions, density dependent quenching of the muonic levels, and transfer processes which depend both on density ϕ and tritium concentration c_t. As the rates for these processes differ widely between atomic shells, and also within each shell, the cascade can take very different routes depending on the actual population of these states. The original prediction of this cascade by Menshikov and Ponomarev [2] has been observed to differ significantly from the experimental results [3-5], in particular, q_{1s} was found to fall much less rapidly with c_t than predicted.

THE MECHANISM: M-SHELL SPLITTING AND MOLECULAR TRANSFER SUPPRESSION

Our present conjecture is based on the observation that the splitting due to vacuum polarization between states in the M-shell of muonic hydrogen is about 70 meV, of the order of thermal energies in the experiments. This splitting is larger than the rates of Stark mixing between these states, so that they should retain approximately good angular momentum. On the other hand, as Stark

© 1989 American Institute of Physics
This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 128.187.97.22 On: Tue, 01 Apr 2014 21:12:21

mixing is believed [6] to be sufficiently fast so that the substates of the M-shell are populated statistically, for densities not less than ϕ=0.01, the population of the 3s, 3p, and 3d states will be strongly temperature dependent below 500 K.

Of course, this observation relies on the fact that thermal equilibrium among the substates of the M-shell is established. We rely here on a detailed study of (μd) elastic and charge-exchange cross sections by Menshikov and Ponomarev [7], which shows that the thermalization rate of excited muonic atoms is $10^{12}s^{-1}$ at ϕ=1, i.e. one order of magnitude larger than the Auger decay rates of M-shell states. Radiative transition rates are about $10^{10}s^{-1}$ for n>2 and hence will not cause any significant deviation from a thermal distribution for densities larger than $\phi = 10^{-2}$. The thermal equilibrium will not prevail in the more strongly split L-shell, since the rate of quenching at T < 500K is smaller than the rate of de-excitation of the 2p-level.

The vacuum polarization splitting of the M-shell would not influence the muon cascade, if the transfer rates had the strengths computed in refs. [2,7]. However, if the observation is combined with the conjecture of strong suppression of the M-shell transfer rate, our analysis shows that a major change in the cascade occurs. At low temperatures, when the 3s state is dominantly populated, the muon falls into the 2p state which rapidly decays to the K-shell by radiation emission. At higher temperatures, a significant fraction of muons is in the 3p state which, after decaying into the metastable 2s state, mostly leads to transfer of the muon to a tritium atom. Thus the combination of M-shell splitting and transfer suppression has the effect of (a) enhancing the population, q_{1s}, of the muonic ground state in deuterium - in agreement with experimental observations, and (b) yielding a functional dependence of q_{1s} that is falling with temperature in accordance with experimental results [3].

It must be noted that, at present, such a reduction in the transfer rate with respect to previous calculations is to a large degree hypothetical but not implausible, given the peculiar properties of the M-shell states: The energy gain in the transfer to the tritium M-shell (5.3eV = 48eV/3^2) is very close to the dissociation energy of the target molecule (4.6eV), and the subshell splittings closely match the rotational energies in the hydrogen molecule. As we shall see, we require a suppression of the M-shell transfer by about two orders of magnitude. At this moment, we do not have a satisfactory, quantitative explanation for such a large suppression factor. (A calculation of the influence of molecular binding along the lines of neutron scattering theory [8] exhibits both enhancing and suppressing effects.) In view of the very delicate molecular structure effects involved in the computation of the M-shell transfer rate we will, therefore, use this suppression as a free parameter of our calculation, and concentrate on analyzing the cycle dynamics in terms of experimentally observed effects.

1S-POPULATION OF MUONIC DEUTERIUM IN A D-T MIXTURE

The relevant level structure and decay scheme of a μd atom is shown in Fig. 1. Level splittings in the L- and M-shell are determined mainly by the vacuum polarization corrections, which amount to a relative shift of 220 meV between the 2s and 2p states, and 66.5 meV and 72.1 meV between the 3s and

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 128.187.97.22 On: Tue, 01 Apr 2014 21:12:21

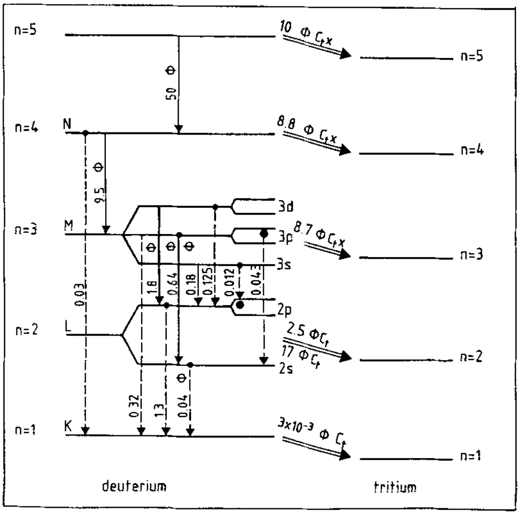

Fig. 1: Level scheme of muonic deuterium with transition and transfer rates. Dashed lines indicate radiative, solid lines Auger transitions.

3p and the 3s and 3d states, respectively. (The values used here also include the much smaller fine structure and hyperfine structure effects.) The strengths of the radiative and external Auger transitions, and of the transfer rates of Menshikov and Ponomarev [2] are shown in Fig. 1, in units of 10^{11} s^{-1}. The Auger and transfer rates depend linearly on the target density ϕ. Note the competition between Auger and radiative transitions of the 3p state, with the radiative decay into the 1s ground state dominating at lower densities (ϕ <0.5). The populations n_{3s}, n_{3p} and n_{3d} are related by,

$$n_{3p} = 3n_{3s}\exp(-\Delta_{3p}/T), \qquad n_{3d} = 5n_{3s}\exp(-\Delta_{3d}/T), \tag{1}$$

where Δ_{3p} and Δ_{3d} are the energy differences to the 3s state, respectively and T is the temperature. Since this splitting influences the statistical populations, there will be a significant temperature dependence of the muonic cascade in deuterium, in particular for $T < 500K$, which in turn influences the kinetics of the muon catalysis cycle.

The rates for the transfer process

$$(d\mu)_n + t \quad \rightarrow \quad d + (t\mu)_n \tag{2}$$

have been calculated [2] for collisions of d atoms with tritium atoms, not molecules. For atom-molecule collisions the transfer process can be strongly influenced by a substantial change of the final state density, as remarked above. For the K- and L-shells the transfer can easily be accompanied by dissociation of the target molecule, whereas those for n=3 and higher shells cannot. Thus for K- and L-shells the values calculated by Menshikov and Ponomarev probably apply, but for the M-shell a molecular suppression mechanism may well be active.

We now turn to consider the effects of M-shell splitting and transfer suppression in muon catalyzed fusion. If the muon reaches the 1s state in deuterium the (dtμ) fusion cycle is significantly delayed due to the very low transfer rate ($3\times10^{8}s^{-1}\phi C_t$) from this state. The (dμ) K-shell population probability is, therefore, a quantity of considerable practical interest. This probability can be

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 128.187.97.22 On: Tue, 01 Apr 2014 21:12:21

written $C_d q_{1s}$ where q_{1s} is the probability for a muon, initially captured by a deuteron, to reach the $(d\mu)$ groundstate. C_d is the fraction of deuterium in the target. Calculations by Menshikov and Ponomarev [2], which are based on uninhibited transfer from all excited states and ignore the splitting of the M-shell, predict very small values for q_{1s}. Aside from the quoted muon catalyzed fusion experiments [3-5], other work, specifically designed to measure q_{1s} and recently carried out [9], has also not been consistent with a small value of q_{1s}.

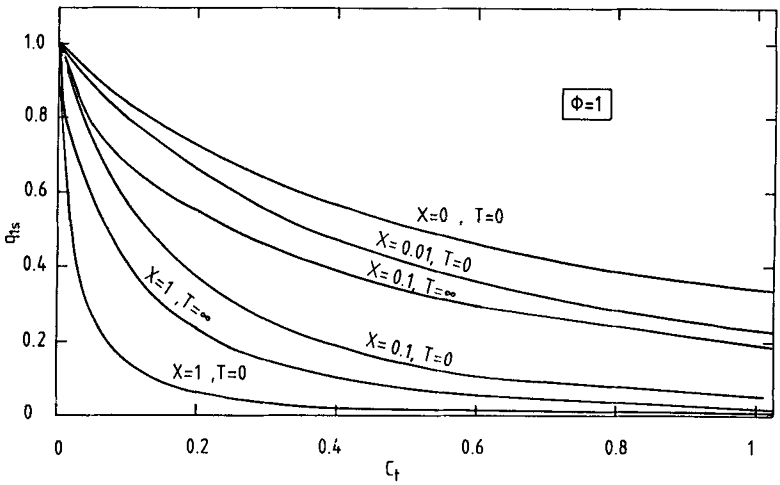

Fig. 2: Fraction of muons reaching the deuterium 1s state for various values of the suppression factor x, as function of tritium concentration for $\phi = 1$.

As discussed above, a molecular suppression factor, denoted by x, is conjectured to strongly inhibit the transfer from states in the $(d\mu)$ M-shell. The dependence of q_{1s} on the reduced strength of the transfer from higher states is shown in Fig. 2, which gives q_{1s} as function of C_t for several values of the parameter x. Our calculation with the value x=1 corresponds to Ponomarev's model, but includes the effects of vacuum polarization on the populations of the L- and M-shell substates. Assuming total transfer suppression (x=0) and a thermal distribution in the M-shell, we find much larger values, e.g. q_{1s}=0.5 at ϕ=1 and C_t =0.5 as compared with q_{1s}=0.08 predicted in the absence of a molecular suppression effect. The dependence on tritium concentration was experimentally measured by Jones et al. [3] for ϕ=0.72 and T=300K, who found $q_{1s}(C_t=0.5)/q_{1s}(C_t=0.04) = 0.72\pm0.15$. Our result for this ratio is 0.67, whereas Menshikov and Ponomarev find the much smaller value of 0.14. The measured ϕ-dependence [3] is also in better agreement with our calculations.

The temperature dependence of q_{1s} is a sensitive probe for the value of x. We find that q_{1s} *decreases* with increasing temperature for x=0, whereas this trend is reversed even for values as small as x = 0.01. In the Menshikov-Ponomarev model (x = 1), modified to include a thermal distribution of the M-shell sublevels, q_{1s} increases by more than a factor 3 within the interval T = 0 - 500 K. (The original Menshikov-Ponomarev model has no temperature

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 128.187.97.22 On: Tue, 01 Apr 2014 21:12:21

dependence.) Using data of Jones et al. [3] for λ_{dt} and q_{1s}, and assuming that λ_{dt} is independent of the temperature instead of q_{1s}, we find that $(q_{1s}^{-1}$-1) is proportional to $(6\pm1)\times10^{-4}$T. This result is displayed in Fig. 3 where it is seen to be in reasonable agreement with the case x = 0, i.e. total suppression of the transfer from $(\mathrm{d}\mu)_{n>2}$ atoms to (molecular) tritium.

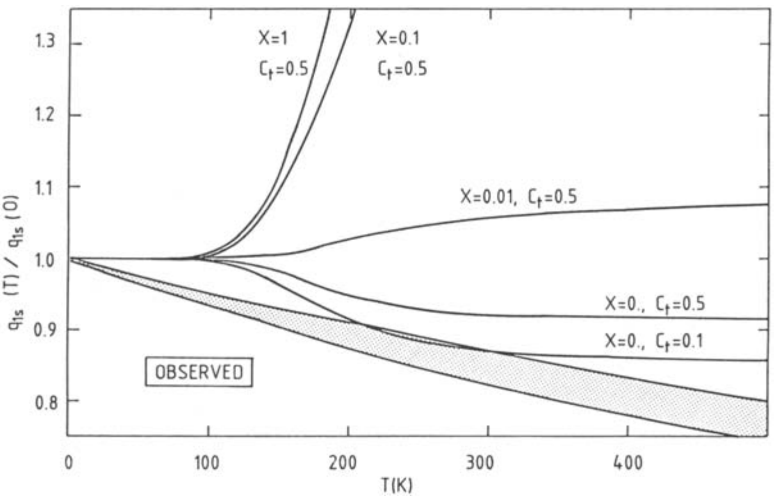

Fig. 3: Temperature dependence of q_{1s} for various values of c_t and x. The observed temperature dependence, indicated by the shaded area, is that of Jones et al. (ref.[3]).

MUONIC X-RAYS IN PURE DEUTERIUM

The muonic cascade in pure deuterium can be employed to verify the T-dependence in the M-shell population. As before, we assume here that the population of the substates of the M-shell is thermally equilibrated for not too low densities ($\phi > 0.1$). Due to continuous fast repopulation of all states within the shell the independent populations n_{3s}, n_{3p}, and n_{3d} decay with the same average rate. However, only muons populating the 3p state contribute to the yield of K_β (3p-1s) radiation. This yield is hence directly proportional to the 3p partial population and the branching ratio into this radiative channel. Decays from both the 3s and 3d states populate the 2p level which also decays into the 1s level. Taking the ratio of the K_β and prompt K_α radiation we eliminate to a large extent our ignorance about other details in the cascade.

Calculations of the ratio K_β/K_α as a function of T for different ϕ show a strong dependence on the precise splitting between the 3p and 3s states indicating the sensitivity of this quantity to the hypothesis of thermal equilibrium in the M-shell. This temperature dependence provides also for a measure of the energy difference between the 3s and 3p states and is hence an indirect measurement of the vacuum polarization effect.

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 128.187.97.22 On: Tue, 01 Apr 2014 21:12:21

CONCLUSIONS

We have shown that a significant temperature dependence of q_{1s} can result from the vacuum polarization splitting in the M-shell of the (μd) atom, if the M-shell transfer rates of muons from deuterium to tritium atoms bound in molecules are strongly suppressed. Our conjecture draws heuristic support mainly from the fact that it allows for a much better description of recent experimental results [3-5].

We note that, if our line of argument for molecular transfer suppression is correct, the suppressing mechanism is probably not active for *atomic* tritium. Calling the fraction of atomic tritium x' and using Fig. 2 we find that $q_{1s} = 0.5 - 10x'$ at ϕ=1. Increasing x' to 1% hence would yield a 20% increase in the cycling rate, for large $\lambda_{dt\mu}$. Obviously, this effect could be used to test the presence of our conjectured molecular M-shell transfer suppression experimentally. For this it would suffice to add a small fraction of atomic tritium to the target. The temperature dependence of the cascade due to vacuum polarization splitting, on the other hand, can be studied by measuring the K_β/K_α ratio in pure deuterium.

Acknowledgement: We would like to thank E.Zavattini for the communication of unpublished results. This work was supported in part by the U.S. Department of Energy.

REFERENCES

1. L.Bracci and G.Fiorentini, Phys. Rep. **86**, 169 (1982).
2. L.I.Menshikov and L.I.Ponomarev, Pis'ma ZhETF **39**, 542 (1984) [JETP Lett. **39**, 663 (1984)].
3. S.E.Jones *et al.*, Phys. Rev. Lett. **56**, 588 (1986).
4. A.N.Anderson, Report at this conference.
5. W.H.Breunlich, Report at this conference.
6. L.Bracci and G.Fiorentini, Nucl. Phys. **A364**, 383 (1981).
7. L.I.Menshikov and L.I.Ponomarev, Z. Phys. **D2**, 1 (1986).
8. S.W.Lovesey, *Theory of Neutron Scattering*, vol.1, Clarendon Press, Oxford 1984.
9. M.Leon, Proc. Int. Symp. on Muon Catalyzed Fusion, Gatchina (1987).

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 128.187.97.22 On: Tue, 01 Apr 2014 21:12:21