Few-Body Syst (2017) 58:1–3
DOI 10.1007/s00601-016-1162-5

Jacek Golak · Roman Skibiński · Henryk Witała · Kacper Topolnicki · Hiroyuki Kamada · Andreas Nogga · Laura E. Marcucci

Muon Capture on ^{3}H

Received: 6 October 2016 / Accepted: 9 November 2016 / Published online: 21 December 2016

Abstract The $\mu^- + ^3\mathrm{H} \rightarrow \nu_\mu + n + n + n$ capture reaction is studied under full inclusion of final-state interactions with the AV18 nucleon-nucleon potential and the Urbana IX three-nucleon force. We employ the single nucleon weak current operator comprising the dominant relativistic corrections to obtain first estimates of the total capture rates based on realistic forces. Our results are compared with older theoretical predictions.

1 Introduction

Muon capture reactions on light nuclei have been investigated for many years. Earlier experimental and theoretical work is described in Refs. [1–3]. More recent theoretical studies, presented for example in Refs. [4–6], has concentrated on the $\mu^- + ^2\mathrm{H} \rightarrow \nu_\mu + n + n$ and $\mu^- + ^3\mathrm{He} \rightarrow \nu_\mu + ^3\mathrm{H}$ reactions, representing the so-called phenomenological approach, the "hybrid" chiral effective field theory (χEFT) approach and the "non-hybrid" χEFT approach. The results obtained within different approaches agreed very well and provided a good description of available experimental data.

In Ref. [7] we combined our experience from the momentum space treatment of electromagnetic processes [8,9] as well as from the potential model approach developed in Ref. [4] and initiated systematic studies of all the $A = 2$ and $A = 3$ muon capture reactions. First we compared results of calculations carried out in the momentum space for the $\mu^- + ^2\mathrm{H} \rightarrow \nu_\mu + n + n$ and $\mu^- + ^3\mathrm{He} \rightarrow \nu_\mu + ^3\mathrm{H}$ reactions with those of Ref. [4] performed in the coordinate space. These two types of calculations employed the AV18 nucleon-nucleon (NN) potential [10] and the Urbana IX three-nucleon (3N) force [11]. In the momentum space the

This article belongs to the Topical Collection "The 23rd European Conference on Few-Body Problems in Physics".

J. Golak (✉) · R. Skibiński · H. Witała · K. Topolnicki
M. Smoluchowski Institute of Physics, Jagiellonian University, 30059 Kraków, Poland
E-mail: jacek.golak@uj.edu.pl

H. Kamada
Department of Physics, Faculty of Engineering, Kyushu Institute of Technology, Kitakyushu 804-8550, Japan

A. Nogga
Institut für Kernphysik (Theorie), Institute for Advanced Simulation, Jülich Center for Hadron Physics and JARA - High Performance Computing, Forschungszentrum Jülich, 52425 Jülich, Germany

L. E. Marcucci
Department of Physics, University of Pisa, 56127 Pisa, Italy

L. E. Marcucci
INFN-Pisa, 56127 Pisa, Italy

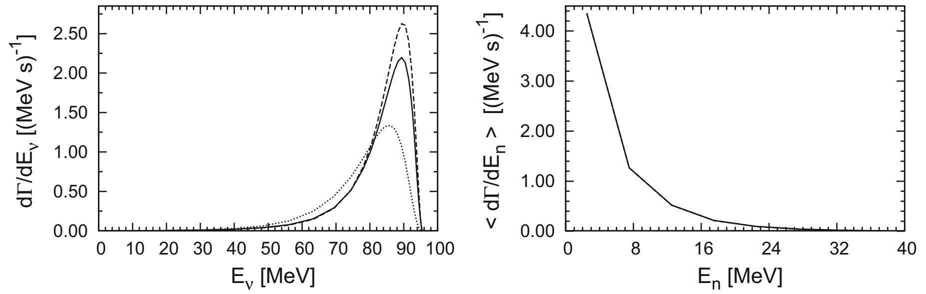

Fig. 1 The differential capture rate $d\Gamma/dE_\nu$ (*left panel*) and the differential capture rate $\langle d\Gamma/dE_n\rangle$ averaged over 5 MeV neutron energy bins (*right panel*) for the $\mu^- + ^3\text{H} \rightarrow \nu_\mu + n + n + n$ process. Results are calculated with the single nucleon current operator including relativistic corrections. *Solid curves* represent predictions obtained with consistent inclusion of the 2N and 3N forces. Additional curves in the *left panel* depict the symmetrized plane wave approximation (*dotted*) and the results obtained with total omission of the 3N force (*dashed*)

weak current operator was taken in the impulse approximation but it was also supplemented by the meson-exchange currents from Ref. [12] [Eqs. (4.16)–(4.39), without Δ-isobar contributions]. A very good agreement was found for the two considered models of the weak current operator.

The two break-up channels in muon capture on ^{3}He were also studied in Ref. [7]. The differential and total capture rates were calculated with the same forces and the single nucleon current operator, providing first reliable estimates of these observables based on a modern nuclear Hamiltonian.

Muon capture on ^{3}H has not been studied so intensively. This reaction, with all uncharged particles in the final-state, would be very difficult to measure because of the radioactivity of the target and due to the meso-molecular complications [1]. Theoretical studies of this reaction were initiated in the 1970s [13–15] and continued in the 1980s [16]. Those early calculations were performed predominantly in the configuration space, using two-nucleon potential models available at that time. Table I in Ref. [16] nicely summarized all the early theoretical predictions.

Very recently, we also investigated this reaction in Ref. [17], since its study was for us the natural next step after the $\mu^- + ^3\text{He} \rightarrow \nu_\mu + n + n + p$ reaction had been considered. The $\mu^- + ^3\text{H} \rightarrow \nu_\mu + n + n + n$ process possesses very interesting features: it allows one to study the neutron-neutron interaction and the three-neutron force acting exclusively in the total isospin $T = 3/2$ state. Our calculations in Ref. [17] were again performed using the AV18 [10] NN potential and the Urbana IX 3N force [11]. Within our momentum space Faddeev framework we incorporated all final-state interactions, retaining only single-nucleon contributions in the weak current operator.

In this contribution we thus present only selected results for the differential and total capture rates in muon capture on ^{3}H. For the details of our formalism and more complete discussion of the results we refer the reader to Ref. [17].

2 Results and Outlook

Our calculations are based on the nonrelativistic kinematics and dynamics. That is why we first checked in Refs. [7,17] that for all the three break-up processes nonrelativistic treatment of kinematics provides a very good approximation. Thus one may hope that also the nonrelativistic dynamical framework is fully justified.

Our results for the $\mu^- + ^3\text{H} \rightarrow \nu_\mu + n + n + n$ process are presented in Fig. 1. First in its left panel we show final-state interaction effects, which turn to be very important. They not only change the plane wave predictions by a factor of 2 but affect also the shapes of the curves and their peak positions. We thus could confirm the findings of Refs. [15,16] obtained with completely different frameworks and much simpler forces. Next, like in Ref. [7], we also study the 3N force effects. They are most visible in the peak area, where the predictions including the 3N force drop by approximately 20%. We checked, however, in Ref. [17] that the 3N force effects come mainly from the initial bound state. The corresponding values of the integrated capture rate are $\Gamma = 36.5\,\text{s}^{-1}$ (calculated without the 3N force) and $\Gamma = 32.6\,\text{s}^{-1}$ (calculated with the 3N force).

Undeniably, further theoretical work and new precision measurements in the whole kinematical region are needed to improve our knowledge about break-up channels in muon capture on ^{3}He and ^{3}H. In the near future we intend to combine the presently used computational techniques with improved dynamical ingredients [18–21] to perform complete chiral EFT calculations at high orders.

Acknowledgements This study was supported by the Polish National Science Center under Grants Nos. DEC-2013/11/N/ST2/03 733 and DEC-2013/10/M/ST2/00420. The numerical calculations were performed on the supercomputer clusters of the JSC, Jülich, Germany.

References

1. Measday, D.F.: The nuclear physics of muon capture. Phys. Rep. **354**, 243 (2001)
2. Gorringe, T., Fearing, H.W.: Induced pseudoscalar coupling of the proton weak interaction. Rev. Mod. Phys. **76**, 31 (2004)
3. Kammel, P., Kubodera, K.: Precision muon capture. Annu. Rev. Nucl. Part Sci. **60**, 327 (2010)
4. Marcucci, L.E., et al.: Muon capture on deuteron and ^{3}He. Phys. Rev. C **83**, 014002 (2011)
5. Marcucci, L.E.: Muon capture on deuteron and ^{3}He: a personal review. Int. J. Mod. Phys. A **27**, 1230006 (2012)
6. Marcucci, L.E., et al.: Chiral effective field theory predictions for muon capture on deuteron and ^{3}He. Phys. Rev. Lett. **108**, 052502 (2012)
7. Golak, J., et al.: Break-up channels in muon capture on ^{3}He. Phys. Rev. C **90**, 024001 (2014)
8. Golak, J., et al.: Electron and photon scattering on three-nucleon bound states. Phys. Rep. **415**, 89 (2005)
9. Skibiński, R., et al.: Different formulations of ^{3}He and ^{3}H photodisintegration. Eur. Phys. J. A **24**, 11 (2005)
10. Wiringa, R.B., Stoks, V.G.J., Schiavilla, R.: Accurate nucleon–nucleon potential with charge-independence breaking. Phys. Rev. C **51**, 38 (1995)
11. Pudliner, B.S., et al.: Quantum Monte Carlo calculations of nuclei with $A < \sim 7$. Phys. Rev. C **56**, 1720 (1997)
12. Marcucci, L.E., et al.: Weak proton capture on ^{3}He. Phys. Rev. C **63**, 015801 (2000)
13. Phillips, A.C., Roig, F., Ros, J.: Muon capture in ^{3}He. Nucl. Phys. A **237**, 493 (1975)
14. Torre, J., Gignoux, Cl, Goulard, G.: Muon capture by the triton. Phys. Rev. Lett. **40**, 511 (1978)
15. Torre, J., Goulard, B.: New approach to transitions from bound to continuum three-nucleon states: the case of muon capture by a triton. Phys. Rev. Lett. **43**, 1222 (1979)
16. Dzhibuti, R.I., Kezerashvili, R.Ya.: Muon capture by the tritium nucleus. Yad. Fiz. **39**, 1109 (1984) [Sov. J. Nucl. Phys. **39**, 700 (1984)]
17. Golak, J., et al.: Muon capture on ^{3}H. Phys. Rev. C **94**, 034002 (2016)
18. Epelbaum, E., Krebs, H., Meißner, U.-G.: Improved chiral nucleon-nucleon potential up to next-to-next-to-next-to-leading order. Eur. Phys. J. A **51**, 53 (2015)
19. Epelbaum, E., Krebs, H., Meißner, U.-G.: Precision nucleon–nucleon potential at fifth order in the chiral expansion. Phys. Rev. Lett. **115**, 122301 (2015)
20. Epelbaum, E., et al.: Three-nucleon forces from chiral effective field theory. Phys. Rev. C **66**, 064001 (2002)
21. Hebeler, K., et al.: Efficient calculation of chiral three-nucleon forces up to N^{3}LO for ab initio studies. Phys. Rev. C **91**, 044001 (2015)