^{14}C Dating Beta Decay and Chiral Effective Field Theory ◇

J.W. Holt , N. Kaiser , and W. Weise

The anomalously long beta decay lifetime of ^{14}C, which makes possible the radiocarbon dating method, has long been a challenge in nuclear structure theory. The transition from the $J_i^\pi = 0^+$, $T_i = 1$ ground state of ^{14}C to the $J_f^\pi = 1^+$, $T_f = 0$ ground state of ^{14}N is of the allowed Gamow-Teller type. Therefore, one would expect from the Wigner SU(4) model of light nuclei that the reduced Gamow-Teller transition matrix element would be on the order 1, yet the known lifetime of $\sim 5730 \pm 30$ years is nearly six orders of magnitude longer than typical allowed transitions in p-shell nuclei. The associated reduced Gamow-Teller transition matrix element must therefore be accidentally small, nearly 2×10^{-3}, making this transition a sensitive test for both nuclear interaction models and nuclear many-body methods.

Very recently, it has been suggested [1] that the ^{14}C beta decay transition matrix element should be particularly sensitive to the density-dependence of the nuclear interaction. We study this problem systematically [2] from the perspective of in-medium chiral effective field theory. For the two-body density-independent component of the nuclear force, we use the low-momentum interaction $V_{\rm low-k}$ derived from the chiral N3LO potential [3] at a decimation scale $\Lambda_{\rm low-k} = 2.1$ fm^{-1}. We then consider Pauli-blocked loop corrections to the in-medium NN scattering amplitude that arise from the leading-order chiral three-nucleon force (3NF). In Fig. 1 we show the six unique contributions generated at one-loop order. The two low-energy constants, c_D and c_E, occurring in the mid- and short-range three-nucleon forces are constrained by fitting the binding energies of ^{3}H, ^{3}He, and ^{4}He.

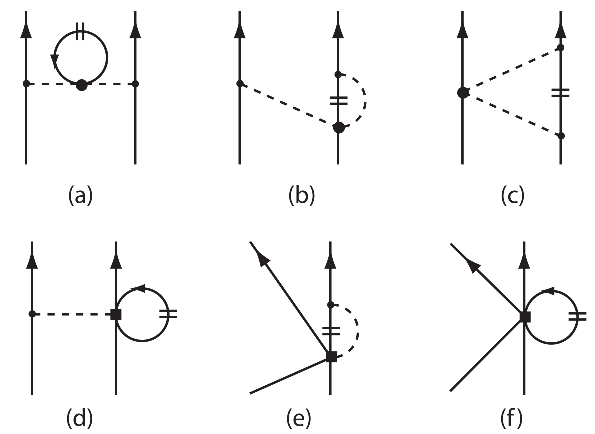

Fig. 1: The six contributions to the in-medium density-dependent NN interaction. The short double-line symbolizes the filled Fermi sea of nucleons in the in-medium nucleon propagator.

Using this model for the in-medium density-dependent NN interaction, we calculate the states of ^{14}C and ^{14}N in the nuclear shell model. These states are treated as two $0p$-holes in an ^{16}O core, and we include the effects of higher-order configurations perturbatively in calculating the shell model effective interaction. The two-pion exchange component of the chiral 3NF generates the three diagrams (a)-(c) in Fig. 1. Evaluation of the Pauli-blocked pion propagator, term (a), and the Pauli-blocked vertex correction, term (b), shows that these two components are large, yet they enter with opposite sign and nearly cancel. Although much smaller in magnitude, the same is true for diagrams (d) and (e), which arise from the medium-range chiral 3NF proportional to the low-energy constant (LEC) c_D. This leaves diagrams (c) and (f) as the two most important contributions, and we discover that it is the latter (proportional to the LEC c_E) that strongly suppresses the ^{14}C decay rate at densities close to that of saturated nuclear matter.

In Fig. 2 we show the calculated Gamow-Teller transition strengths $B(GT)$ from the low-lying states of ^{14}C to the ground state (g.s.) of ^{14}N as a function of the nuclear density. Although most $B(GT)$ strengths are weakly density-dependent, there is a strong suppression of the g.s. to g.s. transition, reaching almost the experimental value at densities close to that of $A = 14$ nuclei. We conclude that in a chiral effective field theory framework, the addition of three-nucleon forces plays an essential role in describing the very long lifetime of ^{14}C.

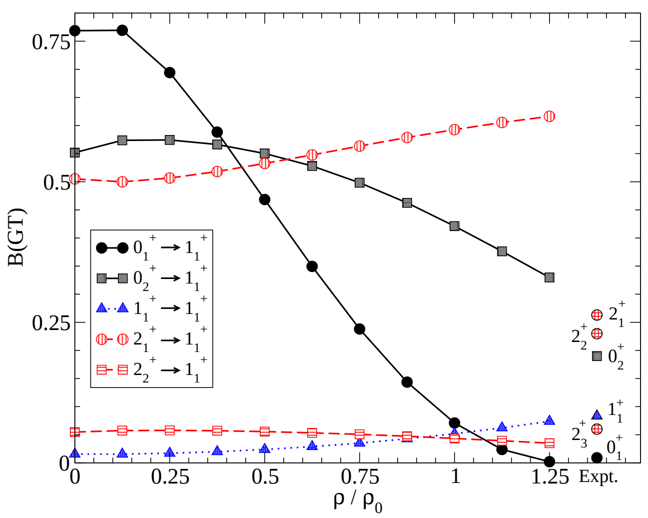

Fig. 2: Caculated $B(GT)$ values for transitions from the states of ^{14}C to the ground state of ^{14}N as a function of the nuclear density. We show for comparison the experimental values determined in [4].

References

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