Uncovering the mechanism of chiral three-nucleon force in driving spin-orbit splitting†

T. Fukui,[*1,*2] G. De Gregorio,[*3,*4] and A. Gargano[*4]

Three-nucleon forces (3NFs) play a crucial role in describing various phenomena of nuclei. For example, the 3NF enhances the spin-orbit (SO) splitting, as indicated in the literature.[1–8] However, the detailed mechanism by which the 3NF contributes to SO splitting has not been fully clarified.

To uncover the aforementioned mechanism, we employed the state-of-the-art 3NFs derived from chiral effective field theory at next-to-next-to-leading order (N^2LO) and decomposed them in terms of the rank of the irreducible tensors forming the three-nucleon potentials. The tensorial structure of the chiral-N^2LO 3NF is summarized in Fig. 1. The decomposed 3NFs were then implemented in the shell-model calculations.[9]

We clarified that the rank-1 component of the 3NF contributes dominantly to the SO splitting of p-shell nuclei. This is because the rank-1 3NF generates a one-body SO potential, the density dependence of which differs from that originating from the two-nucleon SO force.[2] As shown in Fig. 1, the rank-1 3NF arises solely from the two-pion (2π)-exchange process. The low-energy constants (LECs) of the 2π-exchange potentials are relatively well constrained from pion-nucleon scattering compared to those of one-pion (1π)-exchange and contact (ct) terms. Therefore, our conclusion is expected to be robust against the uncertainty of the short-range LECs.

We also revealed an important property of the rank-1 3NF, *i.e.*, an antisymmetric SO (ASO) interaction. The ASO 3NF affects the two-nucleon spin states, which are associated with the subsystem of three-nucleon systems. In particular, the ASO 3NF mixes the singlet and triplet states of two-nucleon spin states, and thus, it can change the quantum entanglement of spin states. Furthermore, the ASO 3NF induces two-nucleon spin canting, similar to the spin canting of magnetic ions driven by the Dzyaloshinsky-Moriya interaction.[10–12]

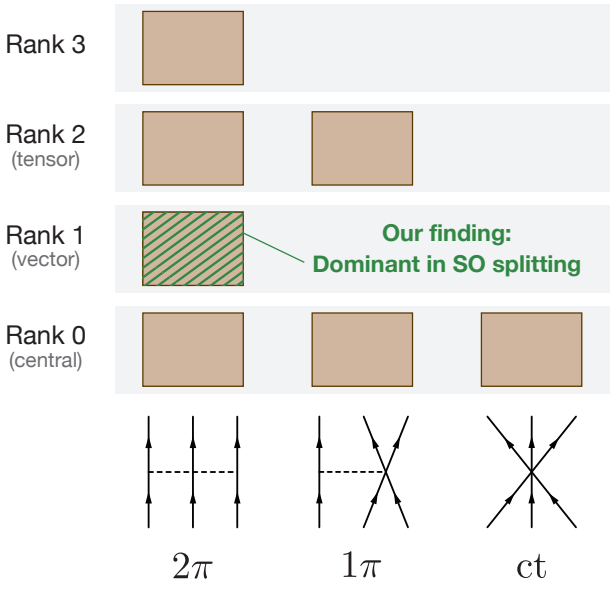

Fig. 1. Classification of chiral 3NF at N^2LO in terms of the rank of tensors forming the potential. We found that the rank-1 component originating from the 2π-exchange process essentially contributes to the SO splitting of light nuclei, whereas 1π-exchange and contact terms were found to have a marginal effect.

References
1) J.-i. Fujita, H. Miyazawa, Prog. Theor. Phys. **17**, 366 (1957).
2) K. Andō, H. Bandō, Prog. Theor. Phys. **66**, 227 (1981).
3) S. C. Pieper, V. R. Pandharipande, Phys. Rev. Lett. **70**, 2541 (1993).
4) T. Otsuka *et al.*, Phys. Rev. Lett. **105**, 032501 (2010).
5) J. D. Holt *et al.*, J. Phys. G **39**, 085111 (2012).
6) T. Fukui *et al.*, Phys. Rev. C **98**, 044305 (2018).
7) N. Kaiser, Phys. Rev. C **68**, 054001 (2003).
8) M. Kohno, Phys. Rev. C **86**, 061301(R) (2012).
9) T. Fukui *et al.*, Phys. Lett. B **855**, 138839 (2024).
10) I. Dzyaloshinsky, J. Phys. Chem. Solids **4**, 241 (1958).
11) T. Moriya, Phys. Rev. Lett. **4**, 228 (1960).
12) T. Moriya, Phys. Rev. **120**, 91 (1960).

† Condensed from the article in Phys. Lett. B **855**, 138839 (2024)

*1 Faculty of Arts and Science, Kyushu University
*2 RIKEN Nishina Center
*3 Dipartimento di Matematica e Fisica, Universitá degli Studi della Campania "Luigi Vanvitelli"
*4 Istituto Nazionale di Fisica Nucleare, Sezione di Napoli

DOI:10.34448/RIKEN.APR.58-019