

# **PFAFFIAN FORMULA FOR PROJECTED HFB STATES WITH MULTI QUASI-PARTICLE EXCITATIONS**

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The Pfaffian, which is a mathematical tool like determinant, has been recently used in nuclear structure calculations with multi quasi-particle excitations on top of the Hartree-Fock-Bogoliubov (HFB) vacuum. The Pfaffian can give a closed and compact formula for a key matrix element of angular momentum projected HFB states with multi quasi-particle excitations.

Before this formula, calculations with four quasi-particle excitations were, indeed, the best we can manage. Beyond four quasi-particle excitations, explicit expressions for necessary formulas become impossible because of combinatorial complexity occurred from the extended Wick's theorem concerning quasi-particle excitations. After the derivation with the Pfaffian, several applications with up to 10 quasi-particle excitations, combined with the projected shell model (PSM), have been possible, and we have recently published about several fact-findings concerning high-spin physics.

In this contribution, we review on our Pfaffian formulation concerning the Balian-Brezin type overlap matrix element with multi quasi-particle excitations. Our formulation is elegant but seems to be rather abstract because it makes full use of Grassmann numbers and Grassmann integrations. On the other hand, we have succeeded an alternative and elementary derivation, though we need the Pfaffian summation formula by a mathematician, J. R. Stembridge, which seems to be unfamiliar for theoretical physicists. This elementary derivation gives us a deeper insight between the Pfaffian and quasi-particle excitations on top of the HFB vacuum and may stimulate further theoretical developments on the HFB wave functions.