Spin entanglement in quasi-elastic and (p,2p) reactions*

H. Matsufuji[1], H. Nishibata[2], H. Sakai[3], and T. Wakasa[1]
[1] *Kyushu University, Fukuoka, Japan*
[2] *University of Teacher Education Fukuoka, Fukuoka, Japan and*
[3] *RIKEN Nishina Center, Wako, Japan*

Entanglement is a distinctive feature of quantum systems. Entanglement entropy of von Neumann type, denoted by $\mathcal{E}(\mathrm{C})$, is commonly used to quantify the degree of entanglement between two quantum particles [1]. It is defined as follows:

$$\mathcal{E}(\mathrm{C}) = H\left(\frac{1}{2}(1+\sqrt{1-\mathrm{C}^2})\right), \tag{1}$$

where $H(x) \equiv -x\log_2(x) - (1-x)\log_2(1-x)$ [3] and $0 \leq \mathcal{E}(\mathrm{C}) \leq 1$. Here, C is called "concurrence", another measure of entanglement strength that is experimentally accessible.

In this context, spin entanglement in nuclei attracts significant interest in relation to di-nucleon correlations in exotic nuclei, quantum information science, and other fields.

Spin entanglement between two nucleons can be generated through nucleon-nucleon scattering. However, determining C from experimentally generated spin entanglement remains a nontrivial task.

Two methods have been proposed to obtain C: one based on the scattering amplitudes by Miller [2] and the other based on the complete spin polarization of one nucleon by Bai [3].

According to Bai's method, we attempted to extract the C by employing the polarizations of one of the outgoing nucleon: $\langle p_{x'}\rangle^2$, $\langle p_{y'}\rangle^2$, and $\langle p_{z'}\rangle^2$. Here, C is defined as

$$\mathrm{C} = \sqrt{1 - \langle p_{x'}\rangle^2 - \langle p_{y'}\rangle^2 - \langle p_{z'}\rangle^2}, \qquad \text{and} \qquad 0 \leq \mathrm{C} \leq 1. \tag{2}$$

Two sets of complete polarization transfer data were used for this analysis. One set is from the quasi-elastic scattering $(\vec{p},\vec{n})$ measurement (QES) by Wakasa [4] corresponding to the p-n scattering in the nucleus, and the other set is from the $(\vec{p},\vec{p}'p'')$ measurement by Noro *et al.* [5] corresponding to the p-p scattering in the nucleus. The polarization transfer data ($D_{\mathrm{SS}'}$, $D_{\mathrm{NN}'}$, $D_{\mathrm{LL}'}$, $D_{\mathrm{LS}'}$, $D_{\mathrm{SL}'}$,) are used to estimate the $\langle p_{x'}\rangle^2$, $\langle p_{'y}\rangle^2$, and $\langle p_{'z}\rangle^2$ values. Then C is extracted using Eq.(2), and subsequently substituted into Eq. (1) to obtain the entanglement entropy $\mathcal{E}(\mathrm{C})$.

We found that the $\mathcal{E}(\mathrm{C})$ depends on the polarization direction of the incident proton and takes values between 0.4 and 1.0. Among these, the maximum values $\mathcal{E}(\mathrm{C})^{\max}$ lie between 0.9 and 1.0, depending on the target nucleus and scattering angles. This target dependence can be interpreted as a dependence on the effective nucleon density at the location where the nucleon-nucleon scattering occurs [5]. Our analysis suggests that $\mathcal{E}(\mathrm{C})$ increases monotonically with effective nucleon density, with an increase of approximately 0.1 observed at 30% of the saturation density. The physical significance of these results remains an open question and is currently under investigation. To our knowledge, this is the first trial to extract $\mathcal{E}(\mathrm{C})$ directly from experimental data.

Some of the results from this study have been previously reported in Ref. [6].

[1] C.H. Bennet *et al.*, Phys. Rev. A **54** (1996) 3824.
[2] G.A. Miller, Phys. Rev. C **108** (2023) L031002.
[3] D. Bai, Phys. Rev. C **109** (2024) 034001.
[4] T. Wakasa, PhD thesis (1997) University of Tokyo, unpublished.
[5] T. Noro *et al.*, Phys. Rev. C **77** (2008) 044604.
[6] H. Matsufuji *et al.*, CNS Summer School 2024 and JPS spring meeting of 2025.

*Sakai will introduce the topics.