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Experimental studies of high density baryonic matter with and without strangeness

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One of the most challenging subjects in nuclear and hadron physics today is to clarify high density baryonic matter in the core of neutron stars. Most of nuclear theories have been constructed referring to experimental data of nuclei with a density equal or less than ρ_0 and cannot be reliably extrapolated to the density larger than ρ_0. In particular, considering the Fermi energy of neutrons and rather strong attraction between a Λ hyperon and a nucleon, Λ's are expected to appear at ˜2-3 ρ_0. The other hyperons (Ξ and Σ) may also appear if their interactions with neutrons are attractive enough. However, appearance of hyperons makes the Equation Of State too soft and results in serious discrepancy against recently-observed heavy neutron stars with 2 solar masses.
To solve this problem called "Hyperon Puzzle", we first need to determine various hyperon-nucleon interactions. The $\Xi - N$ interaction has recently be found attractive from a clear evidence for a $\Xi-$nuclear bound state [1]. Another experimental evidence has been also found at J-PARC in the $^12C(K^-, K^+)$ reaction spectrum, which shows bound-state events of $\Xi-$hypernuclei [2]. In addition, $\Xi-$atomic X-ray measurement has also been attempted at J-PARC. As for the $\Sigma - N$ interaction, we are preparing for a high statistics $\Sigma - p$ scattering experiment. Our recent observation of a very larger charge symmetry breaking effect in A=4 hypernuclei [3] suggests that the ΛN interaction can be different in neutron-rich nuclear matter in neutron stars than in symmetric nuclear matter in hypernuclei.
The most difficult task is to obtain experimental information on nuclear density dependence of baryon-baryon interactions at high density regions, in another word, three-body baryonic forces, which presumably induces strong repulsion. For non-strange nuclear systems, a nucleus-nucleus collision experiment with neutron-rich nuclei has been performed at RIBF, which will provide valuable information on the stiffness of the neutron star EOS at around $2\rho_0$. For higher density regions, however, 3-body forces with hyperons play essential roles. To search for possible effects by the ΛNN force, we are planning to measure the Λ's single-particle energies in various hypernuclei in a wide mass number range with an accuracy of ΔE˜0.1 MeV. Such experiments are proposed at JLab and also planned at J-PARC via the $(e, e'K^+)$ and the (π^+, K^+) reactions, respectively.

[1] K. Nakazawa et al., Prog. Theor. Exp. Phys. 2015, 033D02 (2015).
[2] T. Nagae et al., Proceedings of Science, INPC2016, 038 (2017).
[3] T. O. Yamamoto et al., Phys. Rev. Lett. 115, 222501 (2015).

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