Toward cold and dense antikaonic nuclear clusters

Talk at symposium “Creativity-Innovation—the seed for frontier science” on the occasion of the 80th birthday of Professor Paul Kienle

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Abstract
Experimental search for cold and dense anti-kaonic nuclear cluster systems has been tried since 1998. Recently, an important indication for the most basic cluster $K^- pp$ has been obtained from old data of DISTO on $p + p \rightarrow K^+ + p + \Lambda$ through $\Lambda(1405)$ production as a doorway. This success now triggers an extended search for a double kaonic cluster $K^- K^- pp$. Ultimately we have possibility to investigate multi-kaonic objects and kaonic strangelets in heavy-ion reactions. In this paper I trace my personal reminiscences of collaborative work with Paul Kienle during which I enjoyed the same feeling and excitement as Paul for more than a decade.

Keywords
Dense nuclei · Kaonic nuclear cluster · Multi-kaonic nuclear clusters

1 Discovery of heavy pionic nuclei and partial restoration of chiral symmetry breaking

In early 1990’s when I was struggling with my young colleagues on how to obtain a high-energy deuteron beam to produce deeply bound pionic states in heavy nuclei [1–3], Paul Kienle, then the director of GSI, was constructing a SIS18 synchrotron together with its associated experimental facilities. Since it was dedicated to heavy-ion physics, it would be out of question to expect a deuteron beam from the just born baby, but, surprisingly, the laboratory chef, Paul, proposed us to use the deuteron beam combined with the FRagment Separator ($FRS$) as a forward magnetic spectrometer !! After all, in the first run in 1996 we succeeded in observing the predicted deeply bound pionic states (1s and 2p) in $^{207}$Pb [4]. Successively, we extended our
research to isotope shifts of pionic bound states in Sn isotopes, motivated by the idea of Paul to find experimental signature on chiral symmetry restoration in the nuclear medium \[5, 6\] based on the scenario of spontaneous chiral symmetry breaking of Nambu and Jona-Lasinio \[7, 8\].

A successful experiment toward this direction was carried out \[9\], and the isovector part of the $\pi N$ interaction (represented by a parameter $b_1$) was shown to be significantly enhanced over the free nucleon case, indicating that

$$R_{\pi N}(\rho) = \frac{b_1(\rho)}{b_1(0)} = \frac{|<\bar{q}q>_0|}{|<\bar{q}q>_{\rho}|} \propto \frac{1}{1 - \alpha \rho},$$

(1)

where $\rho = \text{the nuclear density}$, and $<\bar{q}q>_0$ and $<\bar{q}q>_{\rho}$ are $(u, d)$ quark condensates at vacuum and at nuclear density $\rho$, respectively. The density dependence is expressed above with a parameter $\alpha$, which was determined to be $\alpha = (0.36 \pm 0.08) \times \rho_0^{-1}$ \[9\]. In this way, Paul made essential contributions both experimentally and theoretically.

2 Kaonic nuclear clusters predicted: many surprises

In 1998, when we succeeded in finding the ground state of $\pi^-$ in $^{205}$Pb, Paul and myself decided to extend pionic nuclear spectroscopy to kaonic nuclear spectroscopy. By then, already interesting indications of strongly attractive $\bar{K}N$ interactions were known experimentally and theoretically, but how?

The key element was the $\Lambda(1405)$ resonance (abbreviated here as $\Lambda^*$), which was interpreted as the $I = 0 \bar{K}^-p$ bound state. Akaishi constructed complex $I = 0$ and $I = 1 \bar{K}N$ potentials by a $\bar{K}^-p - \Sigma\pi$ coupled-channel procedure, and applied them to few-body nuclear problems by a variational method \[10\]. In this way, deeply bound $\bar{K}$ nuclei (called KNC after Kbar Nuclear Cluster) with moderate decay widths (because of the deep binding no decay to $\Sigma\pi$ final states is possible) were predicted. The most surprising and exciting consequence was an enormously large nuclear density; the strongly attractive force overcomes the short-range $NN$ repulsion, producing exotic nuclei with average nuclear density as much as 3 times the normal density $\rho_0$. Here, for the first time, we showed a new possibility of nuclear systems that violate the law of constant nuclear density, which had been believed to be something like a fundamental law in nuclear physics. Comprehensive unconstrained many-body calculations were carried out \[11, 12\], which revealed more surprises.

3 Structure of $K^- pp$

Figure 1 shows various aspects of $K^- pp$, the most fundamental KNC. This was first predicted to be a strongly bound system \[13\], which possesses all the important features of KNC’s \[14–16\]. Recent Faddeev calculations of this three-body system \[17–19\] also yielded a strongly bound $K^- pp$ mass similar to the YA value \[13\].