WHAT WE HAVE LEARNED FROM MITYA DIAKONOV

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In this short note, I would first like to introduce several conversations that we had with Mitya around the years 2010–2012 when he stayed at RCNP, Osaka. Then a possible interpretation of the parity of the pentaquark is discussed.

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1. Episodes

October 7–December 5, 2012, Mitya was in RCNP (Research Center for Nuclear Physics) as a JSPS (Japan Science Promotion Society) research fellow. Three weeks after he left Japan, the sad news came to us. Mitya passed away on December 26. It shocked us a lot, because it was only two months after we had enjoyed the Kyoto excursion, climbing up to Daimonji Mountain, a scenic place from where we could see the whole Kyoto city. It was a beautiful memory for us.

During his stay, he gave seminars at RCNP, Tokyo, Kyoto, and in other places, enjoying discussions on not only hadron physics but also other various themes. He was very talkative, telling us about his various experiences in physics and life. Here, I would like to bring back a few memories that I remember, not necessarily exactly, but I hope most of them are right, in more or less a chronological order.

1. Mitya was a man of adventure. He went into the forest of Siberia in summer for about a month without telling about his departure to his family. He carried a minimum amount of things to survive, such as a tent, a sleeping bag, some food, *etc.* He stayed and slept in the forest.

He was delighted with talking or even teaching me how to survive by finding eatable things from the forest, preventing harmful mosquitos, and so on.

2. Distill for the poor at home from any kind of homebrew with low alcohol content. Boil it in a pot covered with an umbrella-like lid, slightly wider than the pot, keeping a small space between the pot and the lid. At a lower temperature, the alcohol boils earlier, evaporates, and flows along the lid, falling out of the pot.

3. One snowy day in winter, Mitya was driving a car. Suddenly another car popped up of a deep curtain of snow, rushing at him. Mitya reacted immediately pressing the breaks, but then his car started to spin. After a while, he realized he was safe.

4. Mark Strickman is a person who nowadays speaks in a very intuitive way with an emphasis on the physics picture. However, in many cases, I felt that it was rather difficult to digest. Mitya talked about their young days, when Mark was very theoretical, logical, and strong in mathematics, while Mitya was the opposite. At the end, Mitya concluded: Look, now I speak in a logical way, how we have changed! From this conversation, I learned that in order to draw a physics picture, we need a good understanding of physics.

5. One day he started talking about his "research" in his high-school days. It was about people's heights. He was out on the streets collecting data on people's heights. He talked to me: I found that women's height was more spread out, but can you guess why? His answer was that many women walk in high heels! Another day he asked: Do you know why the Cro-Magnon survived while the Neanderthal became extinct? The Cro-Magnon worked a bit harder, going out more often to find food. His interests were broad, not necessarily related to physics.

6. One of his great achievements is an article entitled "Hard Processes in Quantum Chromodynamics" [1]. Yet he said: Perturbative QCD is simple, which is the reason that I am now working on non-perturbative QCD. Perhaps the instantons are the consequence of it [2, 3].

7. Perhaps, at the end of this list of short conversations, I would like to add how Mitya named $\mathit{\Theta}^+$. Names of baryons use uppercase Greek letters. $\mathit{\Theta}^+$ is the particle sitting at the top of the equilateral triangle of the weight diagram of SU(3) $\overline{10}$. Hence, the letter should be left–right symmetric and the only such letter was $\mathit{\Theta}$.

2. Pentaquark

Here, I would like to briefly comment on how the antidecuplet five-quark $uudd\bar{s}$ configuration emerges. I could imagine that Mitya was thinking about the important role of chiral symmetry and its spontaneous breaking and of non-perturbative dynamics, as a person who proposed the idea of the instanton liquid model [2, 3]. If the breaking is strong enough, as expected in the large-N_c limit of QCD, the pion decay constant f_π which is a measure of the breaking grows as $\sim \sqrt{N_c}$ [4]. In the limit of large N_c, baryons emerge as solitons of a weakly interacting meson theory.

A crucial point is that the (would be) massless Nambu–Goldstone boson, the pseudoscalar and isovector pion, couples to the nucleon via the strong spin–isospin interaction. In the strong coupling limit, the spin and isospin correlate (just as two dipole magnets stick; if one attempts to rotate one of the two magnets, the other will also move together with it), in such a way that the spin and isospin orient themselves in the opposite directions. If the spin and isospin values are the same, the sum of them is zero. This is the hedgehog configuration at the classical level.

Quantum states are then recovered by performing collective rotations in the spin and isospin, or in the flavor SU(3) space. Mitya's idea, and actually what he showed, is that when one rotates in the SU(3) space in the strangeness direction, the antidecuplet $\overline{10}$ multiplet emerges as a low-lying excitation of the hedgehog baryon. Among the ten particles in $\overline{10}$, those located at the three corners (vertices) of the weight diagram are the states that cannot be formed by three quarks, requiring at least five quarks, thus called pentaquarks. From the many-body physics point of view, the idea looks reasonable, because the collective excitations must appear lower than single-particle excitations. A natural consequence of such excitations is that the obtained states carry the same parity as the hedgehog baryon, which is defined to be positive. Spin values should be minimal, hence the expected spin-parity should be $J^P = 1/2^+$. A somewhat non-trivial dynamical consequence is that the decay width of such an excitation is small. This fact triggered the experimental search [5] that has become the starting point of the discussions of exotic hadrons that continue till now.

Since the parity of the state is interesting, I would like to briefly discuss it. In a naive picture of the pentaquark in a quark model, four quarks and one antiquark occupy the lowest S-orbit in a baryon. Hence the parity of such a state is negative in contrast to Mitya's prediction. Then how the positive parity five-quark configuration is possible? For this, we have argued that the chiral interaction among quarks is important [6].

An essential point can be seen in the chiral bag model. Figure 1 shows various energy levels of light (u, d) quarks confined in a spherical bag with the surface interaction between quarks inside the bag and the pion field outside the bag. Due to the hedgehog structure, the light quarks are labeled by the grand spin $K = J + T$, where J and T are the total spin (including orbital angular momentum) and isospin, respectively. The energy levels are functions of the strength of the pion field at the bag surface $F(R)$, the chiral angle of the hedgehog pion field, hence can be plotted as functions of R. The s-quark is not subject to the interaction and hence its energy level is independent of $F(R)$, and also the good quantum numbers are ordinary spin and parity (shown by the blue solid line in the right panel).

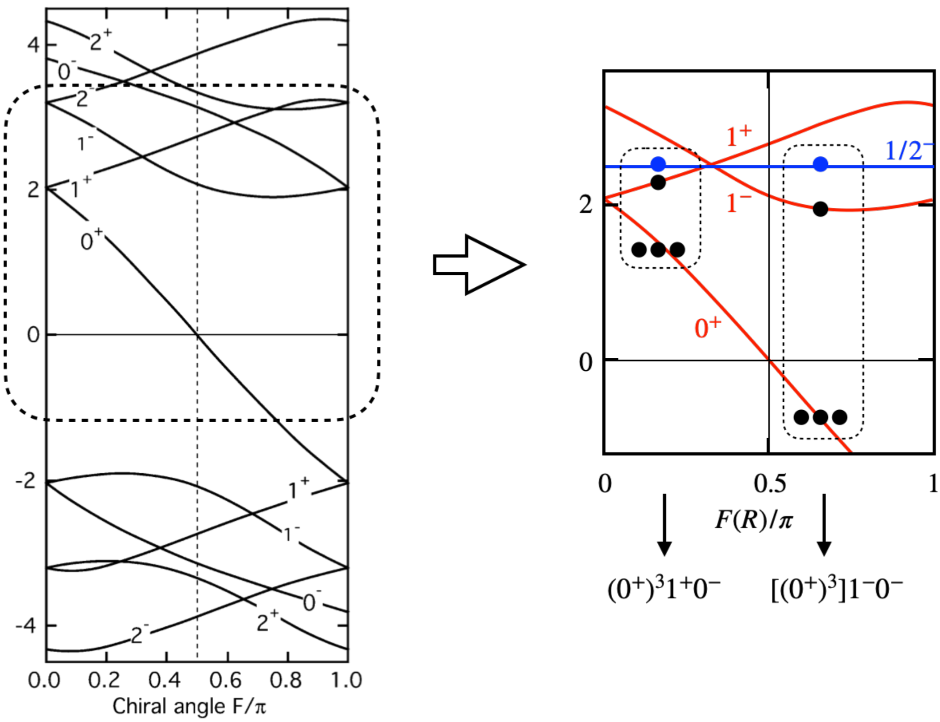

Fig. 1. Left: Various energy levels of quarks in a chiral bag as functions of the chiral angle $F(R)/\pi$, where the quarks are interacting with the hedgehog pion field at the bag surface. Right: The relevant energy levels that are occupied by five quarks $uudd\bar{s}$. Five-quark configurations are shown by the dashed frame surrounding five quarks and the quantum numbers below the arrows at small and large $F(R)$s. The symbol [...] indicates that the 0^+ levels are in the negative energy region.

For a small $F(R)$ at large R, the energy levels are ordered from small to large, $0^+ \to 1^+ \to 1/2^-$(for $\bar{s}$-quark). Therefore, the five-quark configuration is $(0^+)^3 1^+ 1/2^-$, and so the parity is negative. In contrast, for a large $F(R)$ at small R (the limit $R \to 0$ corresponds to the Skyrmion [7]), the ordering of the energy levels is $0^+ \to 1^- \to 1/2^-$(for $\bar{s}$-quark), and the parity is positive. A crucial point is that the level crossing occurs between 1^+ and 1^- levels at $F(R)/\pi \sim 0.3$. Another observation is that for $F(R)/\pi > 0.5$, the lowest 0^+ level is in the negative sea region; the vacuum gets a unit baryon number similar to the Skyrmion.

This could be a microscopic interpretation of the positive parity for the pentaquark state of $uudd\bar{s}$. Whether or not such a configuration is realized, is an important question, what the real world should look like. However, what we have learned from Mitya is the importance to imagining an ideal limit of the theory.

3. Pictures

In closing, I would like to show a few pictures that were taken while Mitya stayed in Osaka in 2012, Fig. 2. The left is the one with Mitya, Hyun-Chul Kim, and myself (from left to right) at the Kyoto University on October 20 (Sat). Starting from the University we went up to Mount Daimonji, which is vaguely recognized behind Mitya in the right top picture. Hyun-Chul and I both remember that after we descended from Mount Daimonji, he said he was very tired. The picture in the top right was taken at Takenaka Inari

Fig. 2. Pictures of Mitya Diakonv, Hyun-Chul Kim, and myself.

Shrine in Kyoto, after Mitya had given a seminar at the Kyoto University. The bottom right one is on the “Three-color road” (the name after the three colors of leaves, green, red, and yellow), about 15-minute walk from RCNP. How could we have imagined what was going to happen after these enjoyable moments?

I would like to thank Hyun-Chul Kim for providing a photo of the three of us and allowing to post it here. I thank him also for his comments.

REFERENCES

[1] Y.L. Dokshitzer, D. Diakonov, S.I. Troian, «Hard processes in quantum chromodynamics», *Phys. Rep.* **58**, 269 (1980).

[2] D. Diakonov, V.Y. Petrov, «Instanton-based vacuum from Feynman variational principle», *Nucl. Phys. B* **245**, 259 (1984).

[3] D. Diakonov, V.Y. Petrov, «A theory of light quarks in the instanton vacuum», *Nucl. Phys. B* **272**, 457 (1986).

[4] E. Witten, «Baryons in the $1N$ expansion», *Nucl. Phys. B* **160**, 57 (1979).

[5] T. Nakano *et al.*, «Evidence for a Narrow $S = +1$ Baryon Resonance in Photoproduction from the Neutron», *Phys. Rev. Lett.* **91**, 012002 (2003), arXiv:hep-ex/0301020.

[6] A. Hosaka, «Pentaquark states in a chiral potential», *Phys. Lett. B* **571**, 55 (2003), arXiv:hep-ph/0307232.

[7] T.H.R. Skyrme, «A unified field theory of mesons and baryons», *Nucl. Phys.* **31**, 556 (1962).