3–6 Exploration of the Exotic Structure of P_c

—Hybrid State with a Mixture of Compact State and Hadron Molecule—

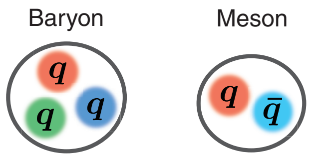

Fig.3-11 Ordinary hadrons; baryons and mesons
Baryon (qqq) and meson ($q\bar{q}$) comprise quarks, where q and $\bar{q}$ denote a quark and an antiquark, respectively. Many experimentally observed hadrons can be classified as either baryons or mesons.

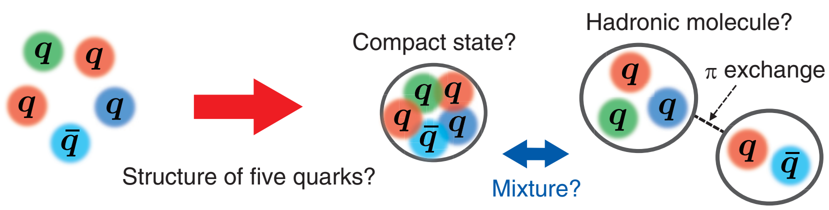

Fig.3-12 Possible five-quark structures: compact state and hadronic molecule
Five quarks are assumed to form a compact state or hadronic molecule. Hadron interactions such as the π exchange force work in the hadronic molecule. Here, P_c was considered a mixture of these two states.

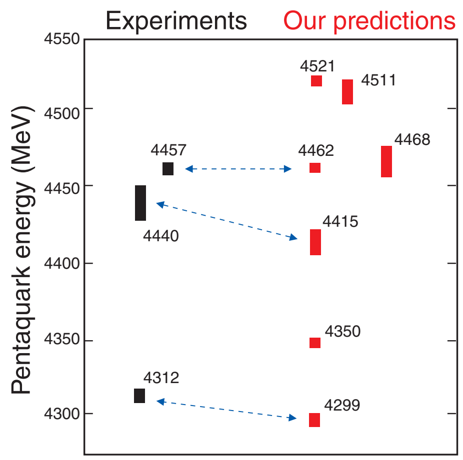

Fig.3-13 Predicted masses and lifetimes of the pentaquarks
Experimental (■) and predicted (■) energies (in mega electron volts (MeV)) are shown, where the center positions of the box corresponds to the mass of the pentaquark (shown next to the box) and the height of the box corresponds to the reciprocal of the lifetime.

Recently, unusually structured hadrons have been reported from accelerator experiments. Ordinary hadrons are classified into baryons and mesons; a baryon comprises three quarks, and a meson comprises a quark and an antiquark (Fig.3-11). Quarks are the elementary building blocks of hadrons, and antiquarks are the antiparticles of quarks. Researchers have discovered hundreds of hadrons have been found. For example, protons and neutrons, which form atomic nuclei, are described as baryons comprising three quarks.

Exotic hadrons, which cannot be explained by the ordinary meson or baryon structure, have been reported recently. Of note is the hadron "P_c" discovered during an experiment at the Large Hadron Collider in Europe, where P_c denotes a pentaquark, i.e., a hadron comprising five quarks. A pentaquark was first reported by SPring-8 in Hyogo, Japan as Θ^+, but its existence was not confirmed. Thus, the observed P_c may represent the first discovered pentaquark.

However, it is not yet understood how the five quarks of P_c form their hadron structure. Therefore, this work aimed to develop a model to theoretically describe the P_c's structure and understand its nature by comparing model predictions with the experimental results.

Two models have been proposed by previous researchers: a compact pentaquark ($c5q$) state in which five quarks form a densely bound state and a hadron molecule in which five quarks are divided into baryon and meson clusters that are loosely bound, similarly as in a molecule (Fig.3-12). However, the $c5q$ state can split into two hadrons of which one is a hadron molecule, thus implying that the two states can mix. Therefore, we have proposed a hybrid model that considers a mixture of the $c5q$ states and hadron molecules. The π exchange force, known to produce attraction binding atomic nuclei, was also introduced in the hadronic molecules.

The energy of the pentaquarks was then predicted using the proposed hybrid model introducing state mixtures (Fig.3-13). The dashed arrows in Fig.3-13 show that the model accurately reproduced the observed mass and lifetime of P_c hadrons. These results indicate that P_c is indeed an exotic state that comprises a mixture of the $c5q$ state and hadron molecule. In addition to these three P_c states, we predict that more pentaquarks are yet to be discovered; future efforts will aim to explore such options and further verify the developed model by analyzing such pentaquarks. Future endeavors will also aim to further understand the P_c structure and continue progressing toward the fundamental problem of how matter of the universe is created from quarks with dynamical processes, such as spontaneous chiral symmetry breaking and confinement.

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Reference

Yamaguchi, Y. et al., P_c Pentaquarks with Chiral Tensor and Quark Dynamics, Physical Review D, vol.101, issue 9, 2020, 091502, 7p.