

Chapter 21

Many-Body Systems in the Strong Interaction

How many bodies are required before we have a problem? G. E. Brown points out that this can be answered by a look at history. In eighteenth-century Newtonian mechanics, the three-body problem was insoluble. With the birth of relativity around 1910 and quantum electrodynamics in 1930, the two- and one-body problems became insoluble. And within modern quantum field theory, the problem of zero bodies (vacuum) is insoluble. So, if we are out after exact solutions, no bodies at all is already too many!

R. D. Mattuck [1]

In the second part of this book we have described how many-body systems may be built out of quarks. The strong interaction is responsible for the binding of these systems, which should be contrasted with the binding of atoms, molecules and solids which are held together by the electromagnetic interaction.

The systems which are built out of quarks – hadrons and nuclei – are complex quantum-mechanical systems. This complexity manifests itself in the systems’ many, apparently mutually incompatible facets. Some aspects of these systems may be understood in a single-particle picture, while some indicate the existence of large sub-structures and others are explained as collective effects of the entire system and finally some are chaotic and only amenable to a statistical description. Each of these concepts, however, only describes a single aspect of these systems.

Quasi-particles At sufficiently low excitation energies, many-body systems, even if they possess a complicated internal structure, may often be described as systems of so-called *quasi-particles*: instead of treating the elementary building blocks, together with their vast variety of mutual interactions, one works with “effective particles” (e.g., electrons and holes in semi-conductors). A large part of the interactions of the fundamental constituents with each other is thus incorporated into the internal structure of the quasi-particles which then, in consequence, only weakly interact with each other.

Collective states Another group of elementary low-energy excitations are the so-called collective states, where many building blocks of a system interfere coherently. Examples of this are lattice vibrations in a crystal (phonons) and waves on the surface of an atomic nucleus.

Chaotic phenomena For greater excitation energies all many-particle systems become more and more complex, until they can no longer be described quantitatively in terms of elementary excitations. Statistical phenomena, which have a universal character, and are thus independent of the details of the interaction, are observed.

Hadrons Little is so far known about the structure of hadrons. Their elementary constituents are gluons and quarks. However, in order to actually observe these experimentally, measurements at “infinitely” large momentum transfers would be necessary. Therefore even in deep-inelastic scattering one only ever observes effective quarks, i.e., many-particle systems. The success of QCD lies in the fact that it is able to quantitatively explain the dependence of the structure functions on the resolution. However, the absolute shape of the structure functions, i.e., hadronic structure, cannot yet be predicted even at large momentum transfers.

The structure of the nucleons depends, however, on the behaviour of quarks at relatively small momenta, since the energies of the excited states are only a few hundred MeV. At such low momentum transfers the coupling constant α_s is so large that the standard QCD perturbative expansion is no longer applicable and we have to deal with a genuine many-particle system.

It has been seen that the spectroscopic properties of hadrons can be described simply in terms of constituent quarks and that one does not need to take the gluons into account. Constituent quarks are complex objects and not elementary particles: we have to understand them as *quasi-particles*. Their properties (e.g., their masses, sizes and magnetic moments) are distinctly different from those of the elementary quarks. It seems that a certain order in hadronic spectroscopy can be obtained by introducing these quasi-particles. The group-theoretical classification of excited states is in fact very successful, but the dynamics are not well understood. It is also not evident whether complex hadronic excitations can be described in the constituent-quark model.

Excited states of hadrons made out of light quarks are known only up to about 3 GeV. The resonances get broader and are more closely packed together as their energy increases. At energies $\gtrsim 3$ GeV, no further resonance structures can be recognised. This could perhaps be a region where chaotic phenomena might be expected. However, they cannot be observed because of the large widths of the resonances.

Collective phenomena have also not yet been observed in hadrons. This may be due to the fact that the number of effective constituents is too small to produce coherent phenomena.

Forces of the strong interaction *Elementary* particles (quarks and leptons) interact through *elementary* forces which are mediated by the exchange of gluons, photons and the W and Z bosons. The forces between systems with internal structure (atoms, nucleons, constituent quarks) are of a more complicated nature and are themselves many-particle phenomena (e.g., the Van der Waals force or covalent binding forces).

To a first approximation the forces of the strong interaction between nucleons or between constituent quarks may be parametrised by effective forces. These are short-ranged and may be, depending upon spin and isospin, either attractive or repulsive. For constituent quarks the short distance interaction seems to be adequately described by one-gluon exchange with an effective coupling constant α_s while at large distances many-gluon exchange is parametrised by a confinement potential. Two-gluon exchange (Van der Waals force) and two-quark exchange (covalent bond) presumably play a minor role in the interaction between two nucleons.

The short-range repulsion is, on the one hand, a consequence of the symmetry of the quark wave function of the nucleon, and, on the other hand, of chromomagnetic repulsion. The dominant part of the attractive nuclear force is mediated by the exchange of $q\bar{q}$ pairs. It is not surprising that these pairs can be identified with the light mesons.

Within the nucleus, this force is also strongly modified by many-body effects (e.g., the Pauli principle). Hence in nuclear physics calculations, phenomenological forces, whose forms and parameters have to be fitted to experimental results, are frequently employed.

Nuclei The idea that nuclei are composed of nucleons is somewhat naive. It is more realistic to conceive of the constituents of the nucleus as quasi-nucleons. The properties of these quasi-particles are similar to those of the nucleons if they are close to the Fermi surface. Some low-energy nuclear phenomena (spin, magnetic moments, excitation energies) can be described by the properties of individual, weakly bound nucleons in the outermost shells or by holes in an otherwise closed shell.

Strongly bound nucleons cannot be assigned to individual states of the shell model. This can be seen, for example, in the very broad states observed in quasi-elastic scattering. In contradistinction, a strongly bound Λ particle inside the nucleus can, it seems, be adequately described as a quasi-particle even in deeply bound states.

Even larger structures in the nucleus may behave like quasi-particles. Pairs of neutrons or protons can couple in the nucleus to form $J^P = 0^+$ pairs, i.e., quasi-particles with boson properties. This pairing is suspected to lead to superfluid phenomena in nuclei, analogous to Cooper pairs in superconductors and atomic pairs in superfluid ^3He . As we have seen, the moments of inertia of rotational states can be qualitatively described in a two-fluid model composed of a normal and of a superfluid phase.

Some nuclear properties can be understood as collective excitations. Such effects can most clearly be observed in heavy nuclei. For example, giant dipole resonances can be interpreted as density oscillations. A nucleus, since it is a finite system, may also undergo shape oscillations. In analogy to solid state physics, quadrupole excitations are described in terms of phonons. The rotational bands of deformed nuclei have an especially collective nature.

At higher energies the collective and quasi-particle character of the excitations is lost. This is the start of the domain of configuration admixtures, where states are built from superpositions of collective and/or particle-hole wave functions. At even higher excitation energies the nuclear level density increases exponentially with the excitation energy and a quantitative description of the individual levels becomes impossible. The great complexity of the levels makes a new description using statistical methods possible.

Digestive In our approach to complex systems we have tried to let ourselves be guided by our understanding of more elementary systems. This helped us to gain a deeper insight into the architecture of more complex systems, and yet we had to introduce new *effective* building blocks, which mutually interact via effective forces, to obtain a *quantitative* treatment of complex phenomena.

Thus in hadron spectroscopy, we used constituent quarks, and not the quarks from the underlying theory of QCD; the interactions between nucleons are best described in terms of meson exchange, not by the exchange of gluons and quarks; in the nucleus effective forces are usually employed instead of the forces known from the nucleon-nucleon interaction and the richness of collective states in nuclei are, even though we have sketched the connection to the shell model, quantitatively better described in terms of collective variables and not in terms of single-particle excitations. This all means that the best description always seems to come from the framework of an “effective theory” chosen according to our experimental resolution. This is by no means a peculiarity of the complex systems of the strong interactions, but is a general property of many-body systems.

Our modern struggles to improve our understanding are fought on two frontiers: physicists are testing whether the modern standard model of elementary particle physics is indeed fundamental or itself “just” an effective theory, and are simultaneously trying to improve our understanding of the regularities of the complex systems of the strong interaction.

And it shall be, when thou hast made an end of reading this book, that thou shalt bind a stone to it, and cast it into the midst of Euphrates.

Jeremiah 51. 63

Reference

1. R.D. Mattuck, *A Guide to Feynman Diagrams in the Many-Body Problem*, 2nd edn. (McGraw-Hill, New York, 1976)