2

Pictures of the nucleus

We currently possess three levels of understanding of the nucleus within the following frameworks [Wa95]:

(I) *Traditional, Non-Relativistic, Many-Body Systems* [Fe71]. This approach uses static two-body potentials fit to two-nucleon scattering and bound-state data. These potentials are then inserted in the non-relativistic Schrödinger equation, and that equation is then solved in some approximation; with few-nucleon systems and large-scale computing capabilities, the equations can now be solved exactly. Electroweak currents constructed from the properties of free nucleons are then used to probe the nuclear system. Although this approach has had a great many successes [Bl52, Ma55, Bo69, Fe71, de74, Pr75, Fe91, Wa95], it is clearly inadequate for a more detailed understanding of the nuclear system.

(II) *Relativistic Many-Body Systems.* A more appropriate set of degrees of freedom for nuclear physics consists of the *hadrons*, the strongly interacting mesons and baryons. There are many arguments one can give for this. For example, the long-range part of the best modern two-nucleon potentials is given by meson exchange, predominantly π with $(J^\pi, T) = (0^-, 1)$, $\sigma(0^+, 0)$, $\rho(1^-, 1)$ and $\omega(1^-, 0)$ [La80, Ma89]. Furthermore, one of the successes of electromagnetic nuclear physics is the unambiguous demonstration of the existence of exchange currents, additional electromagnetic currents in the nucleus arising from the flow of charged mesons between nucleons. In addition, one daily sees copious production of mesons from nuclei in high-energy accelerators.

The only consistent theoretical framework we have for describing such a strongly-coupled, relativistic, interacting, many-body system is relativistic quantum field theory based on a local lagrangian density. It is convenient to refer to relativistic quantum field theory models of the nuclear system based on hadronic degrees of freedom as *quantum hadrodynamics* (QHD).

https://doi.org/10.1017/9781009290616.004 Published online by Cambridge University Press

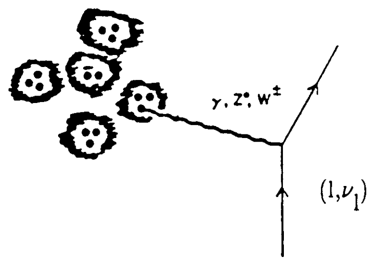

Fig. 2.1. Nucleus as a strongly-coupled system of colored quarks and gluons; electroweak interaction with a lepton.

More generally, one can view such field theories as *effective* field theories for the underlying theory of QCD [Se86, Se97].

(III) *Strongly-Coupled Colored Quarks and Gluons.* Our deepest level of understanding of nucleons, and the nucleus from which they are made, is as a strongly-coupled system of quarks and gluons (Fig. 2.1). Their interactions are described by a Yang–Mills theory [Ya54] based on an internal color symmetry (QCD). This theory has two remarkable properties: it is *asymptotically free*, which means that at very high momenta, or very short distances, the renormalized coupling constant becomes small. This has several consequences. For example, it implies that when in the appropriate kinematic regime, one scatters from essentially free point-like objects. In fact, it was the experimental observation of this phenomenon in deep inelastic scattering (DIS) that drove theorists to hunt for asymptotically free theories [Gr73a, Gr73b, Po73, Po74]. Furthermore, when the coupling is small, one can do perturbation theory. The many high-energy successes of *perturbative QCD* now provide convincing evidence that QCD is truly the underlying theory of the strong interactions.

When one scatters a lepton from a nuclear system, the electroweak interaction takes place through the exchange of one of the electroweak bosons ($\gamma, W^{\pm}, Z^0$), as illustrated in Fig. 2.1. These bosons couple directly to the quarks; the gluons are *absolutely neutral to the electroweak interactions*. Thus every time one observes a gamma decay or beta decay of a nucleus or nucleon, one is directly observing the quark structure of these systems!

The second remarkable property of QCD is *confinement*, which means that the underlying degrees of freedom, quarks and gluons, never appear as asymptotic, free scattering states in the laboratory. You cannot hold a free quark or gluon in your hand. Quarks and gluons, and their strong color interactions, are confined to the interior of the hadrons. At low momenta, or the large distances appropriate for nuclear physics, the renormalized coupling grows large. QCD becomes a strong-coupling theory in this limit.

There are convincing indications from lattice gauge theory (LGT), where strong-coupling QCD is solved on a finite space-time lattice [Wi74], that confinement is indeed a dynamical property of QCD arising from the nonlinear gluon couplings dictated by local color gauge invariance in this non-abelian Yang–Mills theory.