

Nuclear and Particle Physics - Problem Set 7 - Solution

Problem 1)

- a) Partons were discovered in the late 60's with experiments at the Stanford Linear Accelerator Center (SLAC) which scattered high-energy electrons (20 GeV) off proton targets (liquid hydrogen). The inclusive scattering cross sections were measured as a function of scattering angle ($\rightarrow$ squared momentum transfer Q^2) and final electron energy ($\rightarrow$ energy transfer ν). After dividing by the Mott cross section, the structure function $F_2(\nu, Q^2)$ was extracted. It was found that this structure function scaled in the deep inelastic region ($W > 2$ GeV), i.e. $F_2(\nu, Q^2)$ did not depend separately on both variables (ν, Q^2) but only on the combination $x = Q^2/2m\nu$. This was in stark contrast to transition strengths in the resonance region and elastic form factors, which drop precipitously with Q^2 . This finding is analog to Rutherford's experiment which found that α particles could scatter from atoms at large angles, implying that there must be hard, small-sized objects (the atomic nucleus) inside atoms. The SLAC experiments were interpreted as scattering from individual, point-like spin-1/2 partons inside the proton, carrying a fraction x of the proton momentum.
- b) In the constituent quark model (CQM), all known hadrons are interpreted as bound states of a number of constituent quarks. To explain the light hadrons with masses below 2 GeV, one needs to assume that there are 3 types of constituent quarks (Q): up (U), down (D) and strange (S) and their antiquarks. Each quark can carry one of 3 colors (red, green, blue) and the corresponding antiquarks carry anticolors (cyan, magenta, yellow). All baryons (fermions with baryon number $A=1$) are made of 3 quarks (QQQ), while all mesons (bosons with zero baryon number) are made of quark-antiquark pairs. For example, the proton is made from the combination (UUD) and the π^+ meson from a U and D-bar. The CQM also explains the symmetry properties of the hadron wave functions (totally antisymmetric in color, totally symmetric in spin*flavor*space wave function) and thus the spin and parity of hadrons.
- c) *Extra credit* : The CQM has to assume that the quarks have sizeable mass (about 300 MeV/c²) and size to explain the masses of hadrons and their excitation spectra. Also, there are only 3 quarks (and no "sea" quark-antiquark

pairs nor gluons) in the CQM.

On the other hand, the partons discovered in deep inelastic scattering are truly point-like and very light (a few MeV for up and down quarks, and maybe 100 MeV for the strange quark). There are “infinitely” many of them in a given hadron (sea quarks in addition to the 3 “valence” quarks or quark-antiquark pair), and roughly 1/2 of the momentum (mass) comes from gluons.

However, both constituent and “current” (partonic) quarks come in the same flavors and colors, and the *valence* quarks (i.e., the minimum complement of quarks) inside a hadron are of the same type as the constituent quarks.

Therefore, the constituent quarks can be considered as effective “quasi-particles” with the valence quark of the same flavor inside, plus a cloud of sea quarks and gluons.

Problem 2)

- a) $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$: Occurs in nature (muon decay). Changes the charge of a lepton (from $-$ to 0) and therefore is due to the Weak IA.
- b) $\mu^- \rightarrow e^- \gamma$: Has never been observed (but people keep trying). Violates separate muon and electron number conservation.
- c) $\pi^0 \rightarrow e^+ e^-$: Occurs in nature (rare mode of pi-zero decay). Must be due to electromagnetic IA (since the strong IA doesn't couple to leptons like electrons).
- d) $\Lambda^0 \rightarrow p e^- \bar{\nu}_e$: Violates quark flavor conservation but conserves total number of quarks, and electron lepton number. Due to weak IA.
- e) $\Delta^{++} \rightarrow p \pi^+$: Occurs in nature, does not violate any conservation laws, is due to the strong IA (all particles involved are hadrons).
- f) $\mu^- \rightarrow \nu_\mu \gamma$: violates charge conservation (absolutely forbidden).
- g) $p \rightarrow e^+ \bar{\nu}_e$: violates baryon number conservation (absolutely forbidden until further notice).