ELECTROWEAK PROPERTIES OF BARYONS IN A COVARIANT CHIRAL QUARK MODEL

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The proton and neutron electromagnetic form factors and the nucleon axial form factor have been calculated in the Goldstone-boson exchange constituent-quark model within the point-form approach to relativistic quantum mechanics. The results, obtained without any adjustable parameter nor quark form factors, are, due to the dramatic effects of the boost required by the covariant treatment, in striking agreement with the data.

Constituent quark models (CQM’s) provide a useful framework for quantitative calculations of hadron properties in a regime where quantum chromodynamics (QCD) cannot be solved perturbatively. Constituent quarks are effective degrees of freedom described in terms of an Hamiltonian reflecting basic symmetries of QCD. Thus the formalism relies on quantum mechanics with a finite number of degrees of freedom rather than on quantum field theory. However, due to the large value of their kinetic energy constituent quarks are relativistic quasi-particles requiring a relativistic quantum mechanical formulation in terms of unitary representations of the Poincaré group.

Technically, the problem is solved by looking at one of the (unitarily equivalent) forms that are possible when defining the (kinematic) stability subgroup. Here we adopt the point form that has recently attracted some interest in connection with the electromagnetic properties of hadrons. In fact, this form has some advantages. First, the four-momentum operators $P^\mu$ containing all the dynamics commute with each other and can be simultaneously diagonalized. Since the Lorentz generators do not contain any interaction terms, the theory is manifestly covariant. Second, the electromagnetic current operator $J^\mu(x)$ can be written in such a way that it transforms as an irreducible tensor operator under the strongly interacting Poincaré group.
Thus the nucleon charge and magnetic form factors can be calculated as reduced matrix elements of such an irreducible tensor operator in the Breit frame.

Here results are presented as a progress report of a more comprehensive programme dealing with electroweak properties of baryons studied within the CQM discussed in ref. 3 and based on Goldstone-boson-exchange (GBE) dynamics. This type of CQM assumes a pairwise linear confinement potential, as suggested by lattice QCD, with a strength according to the string tension of QCD. The quark-quark interaction is derived from the exchange of pseudoscalar bosons producing the (flavour dependent) hyperfine interaction; in the model only the spin-spin component is utilized, which phenomenologically appears to be the most important in the hyperfine splitting of the baryon spectra. The current operator is a single-particle current operator for point-like constituent quarks. This approach corresponds to a relativistic impulse approximation but specifically in point form. It is called point-form spectator approximation (PFSA).

In fig. 1 the ratio $G_E/G_M$ of the proton electric to magnetic form factor is shown together with the recent TJNAF data 4. In fig. 1 the prediction of the model for the neutron charge form factor is also shown. The solid (dashed) curve is obtained when the theoretical (experimental) value of the proton magnetic moment is used. The difference between the two curves is due to the fact that the calculated proton and neutron charge radii turn out to be in very good agreement with experiment ($r_p^2 = 0.75 \text{ fm}^2$, $r_n^2 = -0.12 \text{ fm}^2$) while the magnetic moments are slightly underestimated ($\mu_p = 2.64 \text{ n.m.}$, $\mu_n = -1.67 \text{ n.m.}$). However, one observes that a very good description of both the proton and neutron e.m. structure is achieved 5. It is remarkable that no further ingredients beyond the quark model wave functions (such as, e.g., constituent quark form factors) have been employed. What is important is that only relativistic boost effects are properly included in point-form relativistic quantum mechanics.

For comparison, results for the neutron charge form factor are also shown when calculated in nonrelativistic impulse approximation, i.e. with the standard nonrelativistic form of the current operator and no Lorentz boosts applied to the nucleon wave functions. Also the case with the confinement potential only has been considered in order to appreciate the role of mixed-symmetry components in the wave functions that are absent without the hyperfine interaction.

A similar approach can be used to study the axial current 6. According to the PCAC hypothesis this current is not conserved. However, one can always split it into conserved and nonconserved parts with the conserved part
containing the axial form factor $G_A$ only. Therefore one can calculate $G_A$ in the same point-form approach used for $G_E$ and $G_M$.

The results are shown in fig. 2, where comparison is made with data obtained from charged pion electroproduction on protons (see ref. 7 and references therein). The nonrelativistic result (dashed line) and the calculation without boost (dot-dashed line) are also shown.
The result is quite good at $Q^2 \neq 0$, while at $Q^2 = 0$ the value of the calculated axial form factor $G_A(0)$ is lower than the value $g_A$ used when fitting the data with a dipole form factor $G_A(Q^2) = g_A/(1 + Q^2/M_A^2)$ involving the axial mass $M_A$. This indicates a deviation of the present results from the usually assumed dipole form. Correspondingly, the axial radius deduced from the slope at $Q^2 = 0$ is lower than the experimental one. With the present model one has $<r_A^2>^{1/2} = 0.520 \text{ fm}$ to be compared with the experimental value $<r_A^2>^{1/2} = (0.65 \pm 0.07) \text{ fm}$ extracted from neutrino experiments and $<r_A^2>^{1/2} = (0.635 \pm 0.023) \text{ fm}$ extracted from pion electroproduction.

References