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Peripheral transverse densities of the baryon octet from chiral effective field theory and dispersion analysis

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Abstract

The baryon electromagnetic form factors are expressed in terms of two-dimensional densities describing the distribution of charge and magnetization in transverse space at fixed light-front time. We calculate the transverse densities of the spin-1/2 flavor-octet baryons at peripheral distances $b = \mathcal{O}(M_\pi^{-1})$ using methods of relativistic chiral effective field theory (χEFT) and dispersion analysis. The densities are represented as dispersive integrals over the imaginary parts of the form factors in the timelike region (spectral functions). The isovector spectral functions on the two-pion cut $t > 4\,M_\pi^2$ are calculated using relativistic χEFT including octet and decuplet baryons. The χEFT calculations are extended into the ρ meson mass region using an N/D method that incorporates the pion electromagnetic form factor data. The isoscalar spectral functions are modeled by vector meson poles. We compute the peripheral charge and magnetization densities in the octet baryon states, estimate the uncertainties, and determine the quark flavor decomposition. The approach can be extended to baryon form factors of other operators and the moments of generalized parton distributions.

Keywords: Electromagnetic form factors; Chiral lagrangians; Dispersion relations; Hyperons; Charge distribution

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1. Introduction

Exploring the spatial structure of hadrons and their interactions is a central objective of modern strong interaction physics. The description of hadrons as extended objects in relativistic space–time enables an intuitive understanding of their structure and permits the formulation of novel approximation methods based on physical distance scales. The most basic information about spatial structure comes from the transition matrix elements (or form factors) of electroweak current operators, which reveal the distributions of charge and current in the system. In non-relativistic systems, such as nuclei in nuclear many-body theory, the form factors are represented as the Fourier transform of 3-dimensional spatial distributions of charge and current at a fixed instant of time $x^0 = \text{const}$. These distributions can be related to probability densities of the N-particle Schrödinger wave function. In relativistic systems such as hadrons the formulation of a density requires separating the structure of the "system" from that of the "probe" in the presence of vacuum fluctuations that change the number of constituents. This is accomplished in a frame-independent manner by viewing the system at fixed light-front time $x^+ = x^0 + x^3$ (light-front quantization) [1–4]. In this framework the form factors are represented in terms of 2-dimensional spatial distributions of charge and current at fixed light-front time $x^+ = \text{const}$. [5–8]. The transverse densities are frame-independent (they remain invariant under longitudinal boosts and transform kinematically under transverse boosts) and provide an objective spatial representation of the hadron as a relativistic system. The properties of the transverse densities of mesons and baryons, their extraction from experimental data, and their explanation in dynamical models have been discussed extensively in the literature [8–12]; see Ref. [13] for a review. An important aspect is that the transverse densities are naturally related to the partonic structure of hadrons probed in high-energy short-distance processes (generalized parton distributions, or GPDs). The densities describe the cumulative charge and current carried by the quarks/antiquarks in the hadron at a given transverse position and represent the integral of the GPDs over the quark/antiquark light-front momentum fraction [6,7,14]; see Refs. [15,16] for a review. This relation places the study of elastic form factors in the context of exploring the 3-dimensional quark–gluon structure of hadrons in QCD.

Of particular interest are the transverse densities at distances of the order $b = \mathcal{O}(M_\pi^{-1})$, where the pion mass is regarded as parametrically small on the hadronic mass scale (as represented e.g. by the vector meson mass M_V) [17,18]. At such "peripheral" distances the densities are governed by the effective dynamics resulting from the spontaneous breaking of chiral symmetry and can be computed model-independently using methods of chiral effective field theory (χEFT) [19,20]; see Refs. [21–23] for a review. The peripheral densities are generated by chiral processes in which the hadron couples to the current operator through soft-pion exchange in the t-channel. The nucleon's peripheral charge and magnetization densities (related to the electromagnetic form factors F_1 and F_2) were studied in Ref. [18] using relativistic χEFT in the leading-order approximation. The densities decay exponentially at large b with a range of the order $1/(2M_\pi)$, and exhibit a rich structure due to the coupling of the two-pion exchange to the nucleon. It was found that the peripheral charge and current densities are similar in magnitude and related by an approximate inequality. These properties are a consequence of the essentially relativistic nature of chiral dynamics [the typical pion momenta are $\mathcal{O}(M_\pi)$] and can be understood in a simple quantum-mechanical picture of peripheral nucleon structure [24–26]. It was also shown that the χEFT densities exhibit the correct N_c-scaling behavior if contributions from Δ isobar intermediate states are included [18,26].