Beyond-Standard-Model Tensor Interaction and Hadron Phenomenology

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We evaluate the impact of recent developments in hadron phenomenology on extracting possible fundamental tensor interactions beyond the standard model. We show that a novel class of observables, including the chiral-odd generalized parton distributions, and the transversity parton distribution function can contribute to the constraints on this quantity. Experimental extractions of the tensor hadronic matrix elements, if sufficiently precise, will provide a, so far, absent testing ground for lattice QCD calculations.

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High precision measurements of beta decay observables play an important role in beyond the standard model (BSM) physics searches, as they allow us to probe couplings other than of the $V-A$ type, which could appear at the low energy scale. Experiments using cold and ultracold neutrons [1–4], nuclei [5–8], and meson rare decays [9] are being performed, or have been planned, that can reach the per-mil level or even higher precision. Effective field theory (EFT) allows one to connect these measurements and BSM effects generated at TeV scales. In this approach that complements collider searches, the new interactions are introduced in an effective Lagrangian describing semileptonic transitions at the GeV scale including four-fermion terms, or operators up to dimension six for the scalar, tensor, pseudoscalar, and $V+A$ interactions (for a review of the various EFT approaches, see Ref. [10]). Because the strength of the new interactions is defined with respect to the strength of the known SM interaction, the coefficients of the various terms, ϵ_i, $(i=S,T,P,L,R)$ depend on the ratio m_W^2/Λ_i^2, where Λ_i is the new physics scale relevant for these nonstandard interactions, and m_W^2 enters through $G_F=g^2/(4\sqrt{2}m_W^2)$. Therefore, the precision with which $\epsilon_i \propto m_W^2/\Lambda_i^2$, is known determines a lower limit for Λ_i. The scalar (S) and tensor (T) operators, in particular, contribute linearly to the beta decay parameters through their interference with the SM amplitude, and they are, therefore, more easily detectable. The matrix elements or transition amplitudes between neutron and proton states of all quark bilinear Lorentz structures in the effective Lagrangian which are relevant for beta decay observables, involve products of the BSM couplings, ϵ_i, and the corresponding hadronic charges, g_i, i.e., considering only terms with left-handed neutrinos,

$$\Delta\mathcal{L}_{\rm eff} = -C_S\bar{p}n\bar{e}(1-\gamma_5)\nu_e - C_T\bar{p}\sigma_{\mu\nu}n\bar{e}\sigma^{\mu\nu}(1-\gamma_5)\nu_e, \tag{1}$$

where $C_S=G_F V_{ud}\sqrt{2}\epsilon_S g_S$, and $C_T=4G_F V_{ud}\sqrt{2}\epsilon_T g_T$. $g_{S(T)}$, characterize nucleon structure; however, at variance with the electroweak currents, there exists no fundamental coupling to these charges in the standard model. Therefore, they cannot be measured directly in elastic scattering processes. This Letter is concerned with an alternative approach aimed at extracting the hadronic charges from experimental data obtained in electron scattering. In previous work, various approaches have been developed to calculate these quantities including lattice QCD [11–15], and most recently, Dyson-Schwinger equations [16,17]. Lattice QCD provides the most reliably calculated values for the isovector scalar and tensor charges with precision levels of $\Delta g_S/g_S \approx 15\%$, and $\Delta g_T/g_T \lesssim 4\%$, respectively. Following the analysis in Ref. [18], these values are well below the minimum accuracy that is required not to deteriorate the per-mil level constraints from decay experiments.

We focus on g_T that appears at leading order in the hadroproduction cross section, and we evaluate both the uncertainty from the experimental extraction of this quantity and its impact on the determination of the elementary tensor coupling, ϵ_T. In order to extract g_T from experiment at the scale $t=(M_n-M_p)^2\approx 0$, which is relevant for BSM physics searches in nuclear and neutron beta decay, we call attention to the fact that this quantity is also the first moment of the transversity distribution [19,20], and that transversity can now be measured in deep inelastic processes. This novel development emerges from recent experimental and theoretical advances in the study of the 3D structure of the nucleon. Current and future planned experiments on dihadron semi-inclusive and deeply virtual exclusive pseudoscalar meson (π^o and η) electroproduction at Jefferson Laboratory [21,22] and COMPASS [23,24] allow us to measure g_T with improving accuracy. The main outcome of the analysis presented here is that the new, more precise measurements of the tensor charge provide, for the first time, a constraint from experiment on the hadronic matrix element in BSM searches.

The tensor form factor is derived from an integral relation involving the transversity (generalized) parton distribution function, or the probability to find a quark with a net transverse polarization in a transversely polarized proton,

$$g_T^q(t, Q^2) = \int_0^1 dx[H_T^q(x, \xi, t; Q^2) - H_T^{\bar{q}}(x, \xi, t; Q^2)], \quad (2)$$

$$g_T^q(0, Q^2) = \int_0^1 dx[h_1^q(x, Q^2) - h_1^{\bar{q}}(x, Q^2)], \quad (3)$$

where, $h_1^{q(\bar{q})}(x, Q^2)$ [19,20] and $H_T^{q(\bar{q})}(x, \xi, t; Q^2)$ [25] are the quark (antiquark) transversity parton distribution function (PDF) and generalized parton distribution (GPD), respectively; $t = (p - p')^2$ is the four-momentum transfer squared between the initial (p) and final (p') proton, $t = 0$ for a PDF which corresponds to the imaginary part of the forward amplitude; Q^2, is the virtual photon's four momentum squared in the deeply inelastic processes; x and ξ are parton longitudinal momentum fractions which are connected to $x_{Bj} = Q^2/2M\nu$, ν being the energy transfer.

The occurrence of these types of integral relations in the chiral-odd sector parallels, in some respect, the Bjorken sum rule [26] connecting the nucleon's helicity structure functions and the axial charge. For the tensor form factor and charge, however, given the nonrenormalizability of the tensor interactions, current algebra cannot be applied. Notice that the QCD Lagrangian does not allow for a proper conserved current associated to the tensor "charge" which is, in itself, somewhat a misnomer. In fact, the tensor charge evolves with the hard scale Q^2, in perturbative QCD (PQCD) [27,28].

Summarizing, to evaluate the hadronic tensor charge, one needs to specify two scales, the momentum transfer squared, which is taken as $t = 0$, and the renormalization scale, which is taken as the scale, Q^2, of the deeply virtual process used to measure the transversity PDF and GPD. When extracting g_T from different sources, it is important to evolve all values to a common scale. In this work, we used next-to-leading-order PQCD evolution equations ([27,28] and references therein) to evolve the experimental values of the tensor charge (all in the range, $Q^2 \approx 1$–$3\ \text{GeV}^2$) to the scale of lattice QCD, $Q^2 = 4\ \text{GeV}^2$ [12–14], in order to be consistent with the previous analysis in Ref. [13]. Although the effect of evolution in the given range of Q^2 is not large compared to the uncertainties of the present experimental extraction, this will become important as the experimental extractions become more precise while spanning a wider range of Q^2 values.

The transversity distributions in Eqs. (2) and (3) parametrize the tensor interaction component in the quark-quark correlation function which reads

$$\int \frac{dz^-}{4\pi} e^{ix\bar{P}^+ z^-} \langle p' S'_\perp | \bar{q}(0) \mathcal{O}_T^\pm q(z) | p S_\perp \rangle |_{z^+ = \mathbf{z}_T = 0}, \quad (4)$$

where $|pS_\perp\rangle$ represents the proton's "transversity state," or a state with transverse polarization obtained from a superposition of states in the helicity basis; the quark fields $(q = u, d)$ tensor structure, $\mathcal{O}_T^\pm = -i(\sigma^{+1} \pm i\sigma^{+2})$, is chiral-odd or it connects quarks with opposite helicities. By working out the detailed helicity structure of the correlation function, one finds that the relevant combination defining transversity is the net transverse quark polarization in a transversely polarized proton.

The isovector components of the tensor hadronic matrix element which are relevant for beta decay correspond to the same tensor structure in Eq. (4), taking the quark fields operator to be local, namely, $\bar{q}(0)\mathcal{O}_T^\pm q(0)$,

$$\langle p'_p, S'_p | \bar{u}\sigma_{\mu\nu} u - \bar{d}\sigma_{\mu\nu} d | p_p, S_p \rangle = g_T(t, Q^2) \bar{U}_{p'} \sigma_{\mu\nu} U_p, \quad (5)$$

where $g_T = g_T^u - g_T^d$; g_T^q represents the tensor form factor for the flavor q in the proton, $g_T^u \equiv g_T^{u/p}$, and $g_T^d \equiv g_T^{d/p}$. From isospin symmetry, one can write

$$\langle p_p, S_p | \bar{u}\sigma_{\mu\nu} d | p_n, S_n \rangle = g_T(t, Q^2) \bar{U}_{p_p} \sigma_{\mu\nu} U_{p_n}, \quad (6)$$

where $p_n \to p_p$, and $p_p \to p_p{}'$.

Transversity cannot be measured in an ordinary deep inelastic scattering process because it is a chiral-odd quantity, but it has been measured with large errors in one-pion jet semi-inclusive deep inelastic scattering (SIDIS) with transversely polarized targets (see review in [29]). Recent progress in both dihadron SIDIS and exclusive deeply virtual meson electroproduction (DVMP) experiments have, however, relaunched the possibility of obtaining a precise experimental determination of g_T^q. The main reason why these processes can provide a cleaner measurement is that they are not sensitive to intrinsic transverse momentum dependent distributions and fragmentation functions, and therefore, they connect more directly to the tensor charge while obeying simpler factorization theorems in QCD.

Dihadron SIDIS off transversely polarized targets

$$l + N \to l' + H_1 + H_2 + X,$$

where l denotes the (unpolarized) lepton beam, N the nucleon target, H_1 and H_2 the produced hadrons, allows one to access the h_1, through the modulation from the azimuthal angle ϕ_S of the target polarization component S_T, transverse to both the virtual-photon and target momenta, and the azimuthal angle of the transverse average momentum of the pion pair ϕ_R with respect to the virtual photon direction. In this process, the observable can be written as the product of h_1^q and a chiral-odd fragmentation function called $H_1^{\sphericalangle q}$ [30,31]

$$F_{UT}^{\sin(\phi_R+\phi_S)} = x \sum_q e_q^2 h_1^q(x; Q^2) \frac{|\boldsymbol{R}| \sin\theta}{M_h} H_1^{\sphericalangle q}. \quad (7)$$

Data for the single-spin asymmetry related to the modulation of interest here are available from HERMES [32] and COMPASS [23,24] on both proton and deuteron targets allowing for u and d quarks flavor separation, whereas the chiral-odd DiFF have been extracted from the angular distribution of two pion pairs produced in e^+e^- annihilations at Belle [33]. Using these data sets, in Refs. [34,35], the transversity PDF has been determined for different functional forms using the replica method for the error analysis. As for future extractions, the dihadron SIDIS will be studied in CLAS12 at JLab on a proton target and in SoLID on a neutron target [21] that will give both an improvement of ~10% in the ratio $\Delta g_T/g_T$ thanks to a wider kinematical coverage and better measurement of the contribution of the d quark. The results from this extraction are shown in Fig. 1.

Deeply virtual exclusive pseudoscalar meson production (DVMP)

$$l + N \to l' + \pi^0(\eta) + N',$$

was proposed as a way to access transversity GPDs assuming a (twist three) chiral-odd coupling ($\propto \gamma_5$) for the $\pi^0(\eta)$ prompt production mechanism [36,38–42]. Three additional transverse spin configurations are allowed in the proton besides transversity, which can be described in terms of combinations of GPDs called $E_T, \tilde{H}_T, \tilde{E}_T$ [25]. The GPDs enter the observables at the amplitude level,

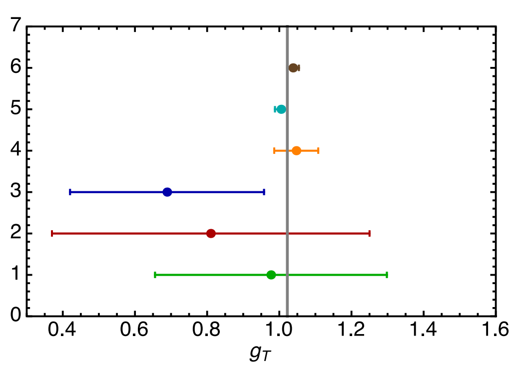

FIG. 1 (color online). Values of the tensor charge, g_T, Eq. (5), as obtained from Lattice QCD at $Q^2 = 4$ GeV^2, and experiments, evolved to $Q^2 = 4$ GeV^2 from their original scale in the range $Q^2 = 1-3$ GeV^2. (1) DVMP [36], (2) DiFF (flexible form) [35], (3) Single pion jet SIDIS [37], (4) RQCD [14], (5) LHPC [12], (6) PNDME [13]. The full line is the weighted average value of g_T.

convoluted with complex coefficients at the leading order, thus, forming the generalized form factors (GFFs). The various cross section terms and asymmetries are bilinear functions of the GFFs. A careful analysis of the helicity amplitudes contributing to DVMP has to be performed in order to disentangle the various chiral-odd GFFs from experiment [43].

The ideal set of data to maximally constrain the tensor charge in the chiral-odd sector is from the transverse target spin asymmetry modulation [36]

$$F_{UT}^{\sin(\phi-\phi_S)} = \Im m[\mathcal{H}_T^*(2\tilde{\mathcal{H}}_T + \mathcal{E}_T)], \quad (8)$$

where ϕ is the angle between the leptonic and hadronic planes, and ϕ_s, the angle between the lepton's plane and the outgoing hadron's transverse spin. In Ref. [36] the tensor charge was, however, extracted by fitting the unpolarized π^0 production cross section [22], using a parametrization constrained from data in the chiral-even sector to guide the functional shape of the, in principle, unknown chiral-odd GPDs. Notice that the tensor charge was obtained with a relatively small error because of the presence of these constraints. The results from this extraction are also shown in Fig. 1.

Finally, in Fig. 1, we also quote the value obtained in single pion SIDIS [37], although this is known to contain some unaccounted for corrections from perturbative evolution [44,45]. The impact on the extraction of ϵ_T, of both the lattice QCD and experimental determinations of g_T is regulated by the most recent limit [46,47]

$$|\epsilon_T g_T| < 6.4 \times 10^{-4} \quad (90\% \text{ C.L.}). \quad (9)$$

Assuming no error on the extraction or evaluation of g_T, yields $\Delta\epsilon_{T,\min} = 6.4 \times 10^{-4}/g_T$. Since the errors on g_T in both the lattice QCD and experimental extractions are affected by systematic or theoretical uncertainty, alternatives to the standard Hessian evaluation have been adopted in recent analyses [18] which are based on the R-fit method [48,49]. By introducing the error on g_T, we obtain $\Delta\epsilon_T \geq \Delta\epsilon_{T,\min}$. Tight limits on ϵ_T require a small relative uncertainty in g_T. We acknowledge that our method cannot reach the precision of a theoretical prediction in lattice QCD. However, as long as ϵ_T stays consistent with the standard model value zero, a moderate $\Delta g_T/g_T \sim 20\%$—which is achievable with these methods using experimental data being taken presently—does not deteriorate the limits set by current beta decay experiments (future JLab experiments will determine $\Delta g_T/g_T$ even more precisely). This situation is illustrated in Fig. 2, where we show ϵ_T vs $\Delta g_T/g_T$ for the various determinations. Let us stress that such per-mil level bounds on the nonstandard tensor coupling are more stringent than those obtained at the LHC [50].

In conclusion, the possibility of obtaining the scalar and tensor form factors and charges directly from experiment

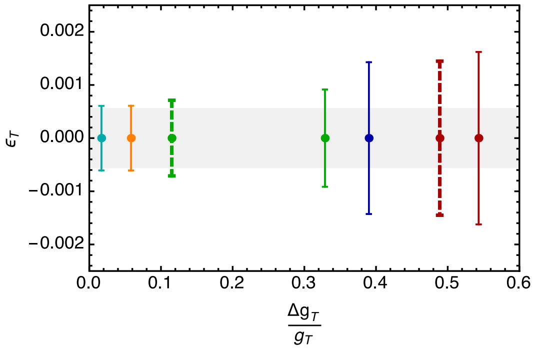

FIG. 2 (color online). Bounds on ϵ_T evaluated using the values of g_T listed in Fig. 1 plotted vs the relative uncertainty $\Delta g_T/g_T$. The color coding for ϵ_T corresponds to the one for g_T in Fig. 1. The dashed lines are for the future projections of the experimental extractions. The grey band gives the uncertainty in ϵ_T assuming $\Delta g_T = 0$ and the average value for g_T from Fig. 1. Notice that the lattice evaluations from Refs. [12,13] are indistinguishable.

with sufficient precision gives an entirely different leverage to beta decay searches. While lattice QCD provides the only means to calculate quantities that are unattainable in experiment, for the tensor charge the situation is different. In this case, the hadronic matrix element is the same as that which enters the DIS observables measured in precise semi-inclusive and deeply virtual exclusive scattering off polarized targets. Most importantly, the error on the elementary tensor coupling, ϵ_T, depends on both the central value of g_T as well as on the relative error, $\Delta g_T/g_T$; therefore, independent of the theoretical accuracy that can be achieved, experimental measurements are essential since they simultaneously provide a testing ground for lattice QCD calculations.

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