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Hyperon Form Factors from $N_f = 2+1$ QCD

M. Göckeler[a], Ph. Hägler[a], R. Horsley[b], Y. Nakamura[a,c], D. Pleiter[d], P. E. L. Rakow[e], A. Schäfer[a], G. Schierholz[d], H. Stüben[f], F. Winter[a], J. M. Zanotti[*,b]

[a] *Institut für Theoretische Physik, Universität Regensburg, 93040 Regensburg, Germany*
[b] *School of Physics and Astronomy, University of Edinburgh, Edinburgh EH9 3JZ, UK*
[c] *Center for Computational Sciences, University of Tsukuba, Tsukuba, Ibaraki 305-8577, Japan*[†]
[d] *Deutsches Elektronen-Synchrotron DESY, 15738 Zeuthen, Germany*
[e] *Theoretical Physics Division, Department of Mathematical Sciences, University of Liverpool, Liverpool L69 3BX, UK*
[f] *Konrad-Zuse-Zentrum für Informationstechnik Berlin, 14195 Berlin, Germany*
E-mail: jzanotti@ph.ed.ac.uk

QCDSF/UKQCD Collaboration

We present results from the QCDSF/UKQCD collaboration for the electromagnetic and semi-leptonic form factors for the hyperons. The simulations are performed on our new ensembles generated with 2+1 flavours of dynamical $\mathcal{O}(a)$-improved Wilson fermions. A unique feature of these configurations is that the quark masses are tuned so that the singlet quark mass is held fixed at its physical value. We use 5 such choices of the individual quark masses on $24^3 \times 48$ lattices with a lattice spacing of about 0.078 fm.

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[*] Speaker.
[†] present address

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1. Introduction

The study of the electromagnetic (EM) properties of hadrons provides important insights into the non-perturbative structure of QCD. The EM form factors reveal information on the internal structure of hadrons including their size, charge distribution and magnetisation.

While the EM form factors of the nucleon have received a lot of recent attention in lattice simulations (see, e.g., [1] for a review), the investigation of the hyperon EM form factors has so far received only limited attention [2, 3]. These, however, are of significant interest as they provide valuable insights into the environmental sensitivity of the distribution of quarks inside a hadron. For example, how does the distribution of u quarks in Σ^+ change as we change the mass of the (spectator) s quark?

Semileptonic form factors of the hyperons provide an alternative method to the standard $K_{\ell 3}$ decays (see e.g. [4]) for determining the CKM matrix element, $|V_{us}|$. This is done by using the experimental value for the decay rate of the hyperon beta decays, $B \to b\ell\nu$

$$\Gamma = \frac{G_F^2}{60\pi^3}(M_B - M_b)^5(1-3\delta)|V_{us}|^2|f_1(0)|^2\left(1+3\left|\frac{g_1(0)}{f_1(0)}\right|^2+\cdots\right), \tag{1.1}$$

where G_F is the Fermi constant, $\delta = (M_B - M_b)/(M_B + M_b)$ describes the size of $SU(3)_{\text{flavour}}$ breaking and the ellipsis denotes terms which are $\mathcal{O}(\delta^2)$ and can be safely ignored [5]. Hence for a determination of $|V_{us}|$, we need to know the form factors, $f_1(q^2)$ and $g_1(q^2)$, at zero momentum transfer ($q^2 = 0$). These can be determined on the lattice and are the subject of the second part of this talk. Earlier quenched and $N_f = 2$ results for $\Sigma^- \to n\ell\nu$ and $\Xi^0 \to \Sigma^+\ell\nu$ can be found in [6, 7].

In this talk we present preliminary results from the QCDSF/UKQCD Collaboration for the octet hyperon electromagnetic and semi-leptonic decay form factors determined from $N_f = 2+1$ lattice QCD.

2. Simulation Details

Our gauge field configurations have been generated with $N_f = 2+1$ flavours of dynamical fermions, using the tree-level Symanzik improved gluon action and nonperturbatively $\mathcal{O}(a)$ improved Wilson fermions [8]. We choose our quark masses by first finding the $SU(3)_{\text{flavour}}$-symmetric point where flavour singlet quantities take on their physical values and vary the individual quark masses while keeping the singlet quark mass $\overline{m}_q = (m_u + m_d + m_s)/3 = (2m_l + m_s)/3$ constant [9]. Simulations are performed on lattice volumes of $24^3 \times 48$ with lattice spacing, $a = 0.078(3)$. A summary of the parameter space spanned by our dynamical configurations can be found in Table 1. More details regarding the tuning of our simulation parameters are given in Ref. [9].

3. Electromagnetic Form Factors

On the lattice, we determine the form factors $F_1(q^2)$ and $F_2(q^2)$ by calculating the following matrix element of the electromagnetic current

$$\langle B(p',s')|j_\mu(q)|B(p,s)\rangle = \bar{u}(p',s')\left[\gamma_\mu F_1(q^2) + \sigma_{\mu\nu}\frac{q_\nu}{2M_B}F_2(q^2)\right]u(p,s), \tag{3.1}$$

Ensemble	κ_l	κ_s	m_π [MeV]	m_K [MeV]	m_N [GeV]	m_Σ [GeV]	m_Ξ [GeV]
1	0.12083	0.12104	481	420	1.257	1.209	1.180
2	0.12090	0.12090	443	443	1.231	1.231	1.231
3	0.12095	0.12080	414	459	1.205	1.240	1.258
4	0.12100	0.12070	377	473	1.175	1.242	1.278
5	0.12104	0.12062	350	485	1.123	1.222	1.280

Table 1: Pion, Kaon and octet baryon masses on $24^3 \times 48$ lattices with lattice spacing, $a = 0.078(3)$ fm

where $u(p,s)$ is a Dirac spinor with momentum, p, and spin polarisation, s, $q = p' - p$ is the momentum transfer, M_B is the mass of the baryon, B, and j_μ is the electromagnetic current. The Dirac (F_1) and Pauli (F_2) form factors of the proton are obtained by using $j_\mu^{(p)} = \frac{2}{3}\bar{u}\gamma_\mu u - \frac{1}{3}\bar{d}\gamma_\mu d$, while the form factors for the Σ and Ξ baryons are obtained through the appropriate substitution, $u \to s$ or $d \to s$. It is common to rewrite the form factors F_1 and F_2 in terms of the electric and magnetic Sachs form factors, $G_e = F_1 + q^2/(2M_N)^2 F_2$ and $G_m = F_1 + F_2$.

If one is using a conserved current, then (e.g. for the proton) $F_1^{(p)}(0) = G_e^{(p)}(0) = 1$ gives the electric charge, while $G_m^{(p)}(0) = \mu^{(p)} = 1 + \kappa^{(p)}$ gives the magnetic moment, where $F_2^{(p)}(0) = \kappa^{(p)}$ is the anomalous magnetic moment. From Eq. (3.1) we see that F_2 always appears with a factor of q, so it is not possible to extract a value for F_2 at $q^2 = 0$ directly from our lattice simulations. Hence we are required to extrapolate the results we obtain at finite q^2 to $q^2 = 0$. Form factor radii, $r_i = \sqrt{\langle r_i^2 \rangle}$, are defined from the slope of the form factor at $q^2 = 0$.

In this talk, we are primarily interested in searching for any $SU(3)$-flavour breaking effects in the octet hyperon form factors. In order to highlight these effects, we will consider ratios of the individual quark contributions to the hyperon radii. For example, the ratio $\langle r_1^2 \rangle_{u_\Sigma} / \langle r_1^2 \rangle_{u_p}$ will tell us about the distribution of the doubly represented (u-)quark in a baryon as we change the doubly-singly represented quark mass splitting (in effect, changing the mass of the spectator quark).

In Fig. 1 we see results for the ratio of the doubly-represented quark's contribution to the Dirac radius of the hyperons plotted as a function of m_π^2. Here we clearly see that the Dirac radii, $\langle r_1^2 \rangle$, of both $u(d)$-quark in the $\Sigma^{+(-)}$ and the s-quark in the $\Xi^{0/-}$ become smaller than that of the u-quark in the proton as we move away from the $SU(3)_{\text{flavour}}$ symmetric point by decreasing (increasing) the light (strange) quark mass. This is particularly interesting in the case of u_Σ, since here the only difference between u_Σ and u_p is the mass of the spectator quark ($d(u)$ in the proton (neutron), s in the Σ), so the fact that the ratio is < 1 is a purely environmental effect.

In Fig. 2 we see a similar picture for the distribution of the singly represented quarks with the $d(u)$-quark in the proton (neutron) having a larger Dirac radius than the $u(d)$-quark in the $\Xi^{0(-)}$ and the s-quark in the Σ having the smallest Dirac radius.

These effects are similar to those seen in an earlier quenched QCD simulation [2], however here the effects are slightly enhanced due to the fact that the strength of the meson loops is suppressed in quenched QCD [10].

Similar results are found for $\langle r_2^2 \rangle$, albeit with larger statistical errors due to the fact that the results need to be extrapolated from $q^2 \neq 0$.