Eur. Phys. J. A **18**, 193–195 (2003)
DOI 10.1140/epja/i2002-10304-5

THE EUROPEAN PHYSICAL JOURNAL A

Electromagnetic properties of baryons in a relativistic quark model

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Received: 30 September 2002 /
Published online: 22 October 2003 –

Abstract. Results on electromagnetic form factors of the nucleon and photon transition form factors of non-strange baryon resonances calculated in a relativistically covariant quark model based on the Bethe-Salpeter equation are presented. The relevance of the instanton-induced quark interaction on these properties is discussed.

PACS. 11.10.St Bound and unstable states; Bethe-Salpeter equations – 12.39.Ki Relativistic quark model – 12.40.Yx Hadron mass models and calculations – 13.40.Gp Electromagnetic form factors

1 Introduction

From the very beginning electromagnetic properties of hadrons played a key role in tests of quark models of baryons. In particular the ratio of the magnetic moments of proton and neutron (experimental value 1.46) is often interpreted as "proving" the correctness of the non-relativistic quark model, which predicts the value 1.5 on the basis of spin-isospin matrix elements only. Also the electric and magnetic form factors of the nucleon have been intensely studied for a long time and constitute important tests for the charge and current distributions inside the nucleon. For a discussion of in particular the neutron form factor, see, *e.g.*, [1]. Most calculations of electromagnetic form factors in the framework of the constituent quark model essentially adopt the wave functions from a non-relativistic treatment of the quark dynamics[1] supplemented by a relativistic prescription for calculating the electromagnetic current matrix elements, see, *e.g.*, [3,4]. Indeed in this manner a remarkable good description of nucleonic form factors can be achieved [5].

In contrast to this in our relativistic quark model we have used the Bethe-Salpeter equation with instantaneous forces, which inherently respects relativistic covariance. On the basis of the amplitudes, obtained by solving the full Salpeter equation, see [6,7,3], the baryonic vertex function (amputated Bethe-Salpeter amplitude) can be reconstructed for any on-shell baryon momentum und thus form factors and various couplings can be calculated in impulse approximation without any additional parameters. The details of the calculation of electroweak form factors of non-strange baryons have been published recently [8]. Here, we shall merely quote the approximations made and briefly discuss also some additional results.

2 Baryonic currents

Insisting on an instantaneous treatment of the quark dynamics on the basis of the full Salpeter equation, even in the presence of two-body interactions, the retardation effects of these can be accounted for only perturbatively. In [9,7,10] it was shown that by the perturbative construction of an effective interaction potential, which parameterises the effects of two-body forces, in lowest order, nevertheless, a very satisfactory description of the baryonic mass spectra up to high masses and high spins can be achieved. The current operators, which enter the computation of form factors then should be calculated consistently with this effective treatment of retardation effects. Again in lowest order, for details see [11,8], the current matrix elements can then approximately be written as

$$\langle \bar{P}|j^\mu(0)|M\rangle = -3\int \frac{\mathrm{d}^4p_\xi}{(2\pi)^4}\frac{\mathrm{d}^4p_\eta}{(2\pi)^4}\bar{\Gamma}_P\left(p_\xi, p_\eta-\frac{2}{3}q\right) \times S_F^1\left(\frac{1}{3}M+p_\xi+\frac{1}{2}p_\eta\right)\otimes S_F^2\left(\frac{1}{3}M-p_\xi+\frac{1}{2}p_\eta\right) \otimes S_F^3\left(\frac{1}{3}M-p_\eta+q\right)\hat{e}\,\gamma^\mu S_F^3\left(\frac{1}{3}M-p_\eta\right)\Gamma_M\left(\boldsymbol{p}_\xi,\boldsymbol{p}_\eta\right),$$

where $\bar{\Gamma}_P, \Gamma_M$ stand for the vertex functions for baryons with on-shell 4-momentum P and $P' = M \equiv (M, \mathbf{0})$ in

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[1] Although often a relativistic form for the single-quark kinetic energy is used and/or some relativistic effects are parameterised in the expressions for the interaction, see, *e.g.*, [2].

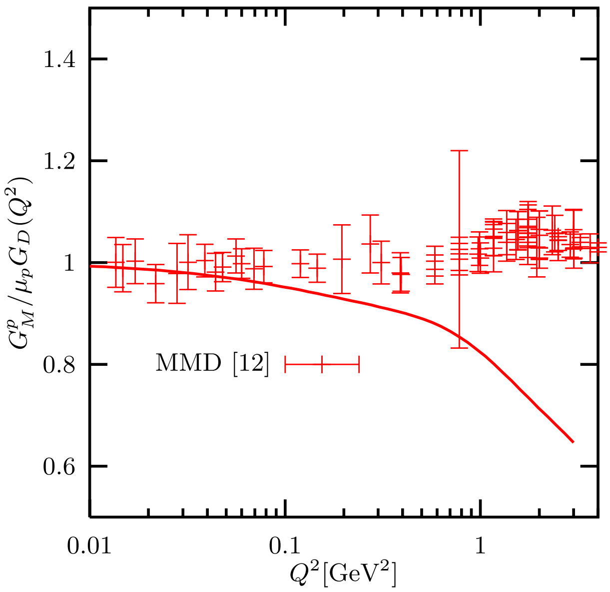

Fig. 1. Magnetic form factor of the proton; experimental data from the analysis of [12].

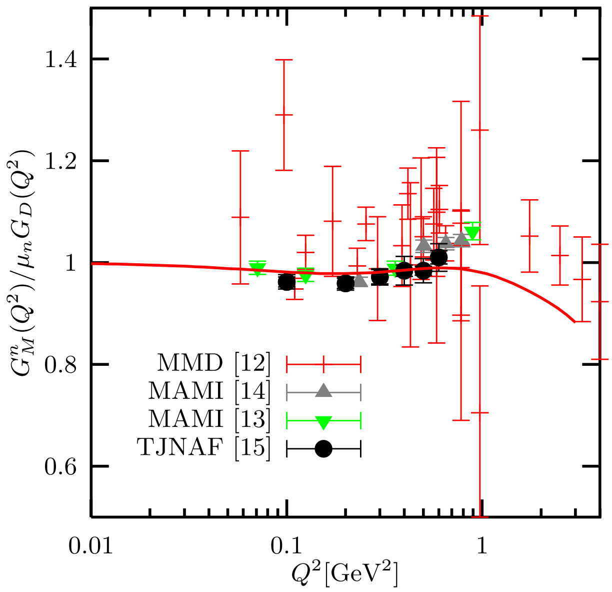

Fig. 2. Magnetic form factor of the neutron; experimental data from the analysis of [12].

the final and initial state, respectively, $q := P - P'$ is the momentum transfer, $\hat{e}$ the quark charge operator and the integration is over the relative 4-momenta of the quarks.

3 Results

Form factors and helicity amplitudes are then calculated by standard formulas [8] . Static properties of the nucleon, such as magnetic momenta, the axial coupling constant and radii are obtained from inspection of the $Q^2 = -q^2$ limit of the corresponding from factors and are in general in excellent agreement with experimental data, again see [8]. We found that the correct relativistic treatment of boosts of our amplitudes is imperative to achieve agreement with the experimental data: If, *e.g.*, we neglect this boost, the value for the magnetic moment of the proton drops by about one nuclear magneton. In this respect the apparent success of the non-relativistic quark model in explaining ratios of magnetic moments must be considered as accidental.

As an example for the quality of our calculations we compare the magnetic form factors of the nucleon relative to a dipole parameterisation in figs. 1 and 2 with experimental data mainly from the compilation of [12]. Although the calculated form factors drop too fast for large momentum transfer[2], the calculation of the neutron magnetic form factor nicely reproduces the shallow minimum around $Q^2 = 0.3$ GeV^2 , recently measured at MAMI [13, 14] and Jefferson Lab [15].

As an illustration of the calculation of electro-excitation of baryon resonances of higher mass and spin

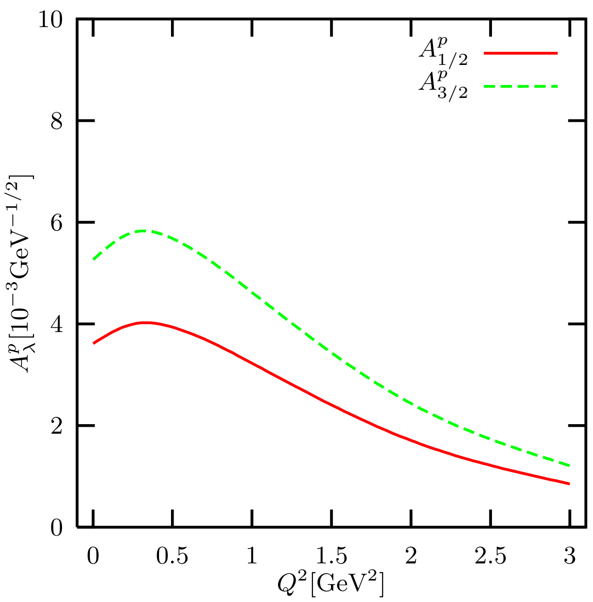

Fig. 3. $D_{15}(1675)$ proton electro-excitation helicity amplitudes.

we present the helicity amplitudes for electro-excitation on the proton for the mass degenerate "parity doublet" $D_{15}(1675)$-$F_{15}(1680)$ in figs. 3 and 4, respectively. We predict that the $D_{15}(1675)$ helicity amplitudes, which however is rather small, drops significantly faster with increasing momentum transfer than the corresponding $F_{15}(1680)$ amplitudes. In the present model this is due to the feature that the former state is (in the harmonic-oscillator nomenclature) dominantly a $L = 1$, $S = \frac{3}{2}$, $1\hbar\omega$-state, for which the instanton-induced interaction

[2] This also applies to the isovector electric form factor of the nucleon, see [8].

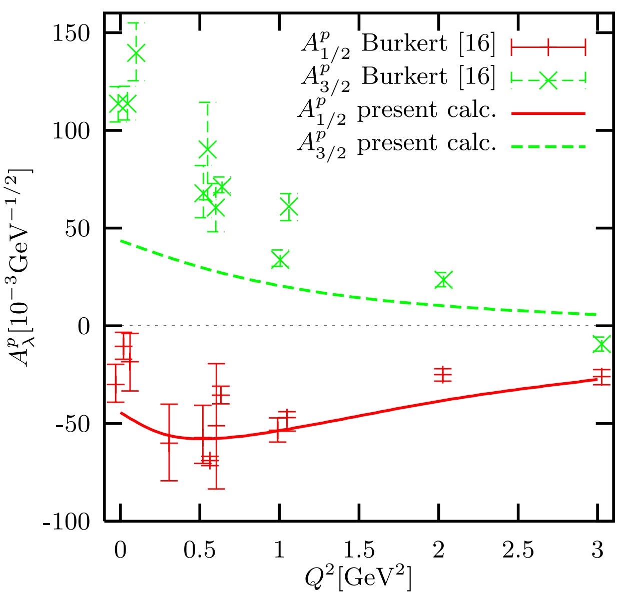

Fig. 4. $F_{15}(1680)$ proton electro-excitation helicity amplitudes.

vanishes, whereas the latter state is mainly a $L = 2$, $S = \frac{1}{2}$, $2\hbar\omega$-state, with scalar diquark correlations from this interaction, which are sufficiently strong to lower this state to a mass almost degenerate with the other state. Furthermore at low Q^2 the experimental data indicate that for this resonance the $A_{\frac{3}{2}}$ amplitude dominates (which is unfortunately not quite reproduced by our calculation) and at large Q^2 the $A_{\frac{1}{2}}$ amplitude is larger, which is also found in the calculation, whereas for the $D_{15}(1675)$-resonance our calculation indicate that both amplitudes have the same magnitude. This different behaviour should be clearly visible in a measurement of an asymmetry $\propto |A_{\frac{1}{2}}|^2 - |A_{\frac{3}{2}}|^2$ in dependence on Q^2.

In conclusion we think that we have demonstrated, that a fully relativistic treatment of the quark dynamics and their electromagnetic couplings on the basis of the instantaneous Bethe-Salpeter equation with quark forces from a confinement potential and an instanton-induced interaction indeed leads to an encouraging description of the major features of baryonic excitations, which certainly still can and, in view of the approximate treatment of retardation effects from the two-body interaction, must be improved.

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