Quark model description of hadrons

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Abstract. In this contribution I will try to give an overview of what has been achieved in constituent quark models of mesons and baryons by a comparison of some selected results from various ansätze with experimental data. In particular I will address the role of relativistic covariance, the nature of the effective quark forces, the status of results on electromagnetic and strong-decay observables beyond the mere mass spectra, as well as some unresolved issues in hadron spectroscopy.

INTRODUCTION

Although some appreciable progress has been made in ab initio calculations of low-lying baryon resonances within the lattice gauge approach, still the only comprehensive description of the complete known spectrum of hadrons (focussing on light quark flavours) with masses up to 3 GeV, which addresses such issues as linear Regge-trajectories, parity doublets in the baryon spectrum, the conspicuous structure of scalar excitations of hadrons, is in fact the constituent quark model, which assumes that the majority of meson and baryon excitations can be effectively described as $q\bar{q}$– and $q^3$– bound states of (constituent) quarks and that the coupling to more complicated configurations (such as strong decay channels) can be treated perturbatively. Although recent experimental findings hint at the existence of exotic meson and baryon resonances, this scheme at least constitutes a framework to judge what is to be considered as exotic.

Since quarks, even when adopting constituent, effective quark masses, move in hadrons with velocities which are a significant fraction of the velocity of light and most non-static observables involve processes at rather large momentum transfers, the quark model description should be based on the usual concepts of quantum field theories. In spite of this, traditionally the quark dynamics in quantitative constituent quark models has been formulated on the basis of the non-relativistic Schroedinger equation and relativistic corrections have at best been parameterized. Recent calculations on electromagnetic form factors elucidated the role of Poincare invariance in calculating electromagnetic currents.

The ultimate goal of any hadron model is to obtain a unified description of

• Mass spectra of (e.g. light-flavoured) hadrons from the ground states up to the highest masses < 3 GeV and highest angular momenta $J < 8$ observed, addressing such issues as: Regge-trajectories, scalar excitations, (pseudo)scalar mixings (for mesons), parity doublets (for baryons), undetected resonances, etc.
electroweak properties, such as electroweak form factors, radiative decays and transitions, semi-leptonic weak decays, etc.

• strong (two-body) decays and interactions.

Even within the framework of the constituent quark model, the various approaches found in the literature do not only differ appreciably with respect to their scope, but also in the modelling of the effective quark interactions used and in the assumptions concerning the dynamical equations. Here we can distinguish between (a) field theoretical approaches, which implement relativistic covariance in the basic set-up, such as: Lattice-gauge theory of QCD, Dyson-Schwinger/Bethe-Salpeter approaches relying on a parametrization of the infrared gluon propagator, see e.g. [1], instantaneous approximations to this, on the basis of a parametrization of confinement and using instanton-induced interactions, which allows for addressing the complete light-flavoured hadron spectrum and not merely the ground and some lower excited states and (b) quantum mechanical approaches on the basis of the Schrödinger equation with relativistic corrections using confinement potentials and effective quark interactions based (alternatively) on O(ne) G(luon) E(xchange), see e.g. [4] or G(olddone) B(oson) E(xhange), see e.g. [2]. Here Dirac’s instant-, point- or front- formulation of relativistic quantum mechanics is invoked to subsequently calculate various currents.

MESONS

In the following we will sketch the various assumptions and approximations made in constituent quark models by focusing on mesons: Adopting the framework of quantum field theory mesons are described as bound $q\bar{q}$ states with $M^2 = \bar{P}^2$, described by the Bethe-Salpeter amplitude $\xi_{\alpha\beta}(x_1, x_2) := \langle 0 | T \{ \psi_\alpha(x_1) \psi_\beta(x_2) \} | \bar{P} \rangle$, which enters in a set of coupled equations which mutually determine the full propagators for the fermions and exchange bosons and the dressed vertex functions involved. In practice one truncates this set of equations by making an Ansatz for some $n$-point function and solving the equations (Bethe-Salpeter-Equation (BSE) for two particles or the Dyson-Schwinger-equation (DSE) for the self-energy) of lower order. In particular, based on an effective gluon propagator with a specific infrared behaviour this leads to the renormalization-group-improved rainbow-ladder approach [1], of which we will quote some interesting results. In a simplified Ansatz one can refrain from solving the DSE and assume that the fermion propagator has the free form $S(p) \approx i \left[ \gamma^\mu p_\mu - m + i\epsilon \right]^{-1}$ and to account for the self-energy contributions by introducing a constituent mass $m$. Furthermore one could assume that the irreducible interaction kernel is given by a single gluon exchange (OGE) in Coulomb gauge, possibly with a running coupling, where a Coulomb part of the interaction is instantaneous, and thus in the no-retardation limit $k^2 \to -|\vec{k}|^2$ arrive at an instantaneous OGE–potential. Such instantaneous interaction kernels allow for a parametrization of confinement by a string-like potential and, defining the Salpeter-Amplitude as $\Phi(\vec{p}) = \int d\rho^0 \frac{\rho^0}{2\pi} \chi(\rho^0, \vec{p}) \bigg|_{(\rho^0 = M, \vec{p})}$, one then arrives at the Salpeter-Equation...
(instantaneous Bethe-Salpeter Equation)

\[
\Phi(\bar{p}) = \int \frac{d^3p}{(2\pi)^3} \frac{\Lambda_1^-(\bar{p}) \gamma^0 [V(\bar{p}, \bar{p}') \Phi(\bar{p}')] \gamma^0 \Lambda_2^+(\bar{p})}{M + \omega_1 + \omega_2} - \int \frac{d^3p}{(2\pi)^3} \frac{\Lambda_1^+(\bar{p}) \gamma^0 [V(\bar{p}, \bar{p}') \Phi(\bar{p}')] \gamma^0 \Lambda_2^-(\bar{p})}{M - \omega_1 - \omega_2},
\]

with the projectors \(\Lambda^\pm(\bar{p}) = (\omega_0(\bar{p}) \pm H_5(\bar{p}))/2\omega_0(\bar{p})\), the Dirac Hamiltonian \(H_5(\bar{p}) = \gamma^0 (\bar{p} \cdot \vec{p} + m_i)\) and where \(\omega_0(\bar{p}) = \sqrt{m_i^2 + \bar{p}^2}\). If one now drops the first term on the r.h.s. of Eq. (1) one arrives at the reduced Salpeter-equation, which then has the form of a Schrödinger equation with relativistic kinetic energy and relativistic corrections to the potential (contained in \(\Lambda^\pm\)). This can be considered the starting point of virtually all “relativized” constituent quark models.

Pioneering work in this spirit was performed already almost two decades ago by the group around Nathan Isgur both for mesons, see [3], and later on for baryons, see [4] and references therein. Here it was assumed that the quark interactions in hadrons can effectively be described by a linear confinement potential and spin-dependent parts of one gluon exchange; relativistic effects in the interactions were accounted for by parametrizations. This also holds for the description of annihilation contributions to pseudoscalar mixings. The scope of the calculation e.g. for mesons is a unified description of all resonances, both with light and with heavy flavours, and also includes a calculation of a multitude of electroweak and strong decay observables, which in spite of the more than a dozen model parameters can still be considered as rather efficient.

On the other hand one can also take the full Salpeter equation as a starting point for constituent quark model calculations: here the instantaneous interaction kernel consists of the Fourier transform of a string-like linearly rising confinement potential with an appropriate Dirac structure which avoids large spin-orbit splittings, supplemented by a spin-flavour dependent interaction motivated by instanton effects, see [6]. The latter has the decisive advantageous property to incorporate the \(U_A(1)\) anomaly quantitatively and thus to account immediately for the splitting and mixing of (pseudo)scalar mesons. The total number of parameters in this approach amount to seven. As an example a comparison of the isoscalar mass spectrum for two versions of the confinement potential (Model \(\mathcal{A}\) and Model \(\mathcal{B}\) employing confinement Dirac structures \(\frac{1}{2} (I \otimes I - \gamma_0 \otimes \gamma_0)\) and \(\frac{1}{2} (I \otimes I - \gamma_5 \otimes \gamma_5 - \gamma_\mu \otimes \gamma_\mu)\), respectively) with experimental data and the results from the calculation of Godfrey and Isgur is given in Fig. 1. Apart from the scalar sector the results are rather similar. While the ‘relativized’ quark model calculation resort to the rather \textit{ad hoc} ‘mock-meson’ method, in the field theoretical approaches based on the Bethe-Salpeter equation the calculation of decay amplitudes in the Mandelstam-formalism is straightforward and parameter free, albeit numerically tedious. A comparison of the results for pseudoscalar decay constants is given in Table 1 for some radiative transitions in [2] and of the \(\omega \rightarrow \pi \gamma\) and \(K^* \rightarrow K \gamma\) transition form factors in Fig. 2. The Dyson-Schwinger approach leads to an excellent description of some observables, but at the time is unfortunately limited to calculations on properties of the lowest pseudoscalar and vector mesons mainly. This restriction does not apply to the instantaneous Bethe-Salpeter approach, which simultaneously describes the whole mass spectrum and
FIGURE 1. Spectrum of S- and P wave isoscalar mesons. From left to right each column (of fixed spin \( j \), parity \( \pi \) and charge parity \( c \)) displays the results from the Godfrey-Isgur 'relativized' calculation \([3]\), the experimental resonance position with a box indicating the error, and two versions of the relativistic calculation on the basis of the Salpeter equation with instanton-induced forces \([6]\).

TABLE 1. Pseudoscalar decay constants in [MeV]

|        | Model \( \mathcal{A} \) | Model \( \mathcal{B} \) | DSE     | Exp.  | OGE   |
|--------|--------------------------|--------------------------|---------|-------|-------|
| \( f_\pi \) | 212                      | 219                      | 132     | 130.7 ± 0.46 | 184   |
| \( f_K \)  | 248                      | 238                      | 154     | 159.8 ± 1.84 | 235   |

without introducing new parameters does fairly well also for observables at higher momentum transfer, see \([6]\). Such observables were not calculated in the relativized quark model, nevertheless the \textit{ad hoc} “mock-meson method” gives a remarkable description of a multitude of other experimental data.

BARYONS

Although some pilot studies on (ground states of) baryons as \( q^3 \)-systems have been done in the Dyson-Schwinger approach within a diquark-quark picture \([1]\), the majority of constituent quark models of baryons still rely on the non-relativistic treatment with (some) relativistic corrections. If one insists on a description of the whole mass spectrum implementing relativistic covariance both in the quark dynamics and in the calculation of currents needed for decay observables, again, as for mesons, the instantaneous Bethe-Salpeter equation seems to be an appropriate starting point. Baryons are thus described
TABLE 2. Decay widths in [keV] of radiative meson transitions

| Decay                       | Model A | Model B | DSE  | Exp.  | OGE  |
|-----------------------------|---------|---------|------|-------|------|
| $\rho^\pm \to \pi^\pm \gamma$ | 35      | 21      | 53   | 67$^\pm$9 | 67$^\ast$ |
| $\rho^0 \to \pi^0 \gamma$   | 35      | 21      | 117$^\pm$30 | 67     |
| $\rho^0 \to \eta \gamma$    | 50      | 40      | 57$^\pm$11 | 51     |
| $\omega \to \pi^0 \gamma$   | 315     | 185     | 479  | 717$^\pm$42 | 642   |
| $\omega \to \eta \gamma$    | 5.5     | 4.4     | 5.5$^\pm$0.8 | 5.4    |
| $K^{\pm} \to K^{\pm} \gamma$ | 48      | 29      | 90   | 50$^\pm$5   | 67     |
| $K^{*0} \to K^{0} \gamma$   | 102     | 70      | 130  | 117$^\pm$10 | 118   |
| $\eta' \to \rho^0 \gamma$   | 87      | 28      | 60$^\pm$5   | 135    |
| $\eta' \to \omega \gamma$   | 9.7     | 3.1     | 6.1$^\pm$0.8 | 13.4   |
| $\phi \to \eta \gamma$      | 58      | 35      | 58$^\pm$2   | 66     |
| $\phi \to \eta' \gamma$     | 0.01    | 0.08    | 0.30$^\pm$0.16 | 0.26   |

$^\ast$ fitted

FIGURE 2. Left: comparison of $\omega - \pi - \gamma$-transition form factor calculated in the Dyson-Schwinger approach (DSE) of [1] with experimental data in the time-like region, the results from the instantaneous Bethe-Salpeter approach (BSE) and simple $\omega$-vector meson dominance; Right: predictions for the charged ($F^+$) and neutral ($F^0$) $K^* - K - \gamma$-transition form factors

by the homogeneous Bethe-Salpeter equation with three-particle and two-particle instantaneous interaction kernels, which implement confinement and a spin-dependent interaction to account for the major mass splittings. Again the assumption of effective constituent quark propagators of the free form together with an approximate treatment of the two-body interactions [7] allows to formulate the dynamics in terms of Salpeter amplitudes (e.g. in the rest frame of the baryons): $\Phi_M(\vec{p}_\xi, \vec{p}_\eta) := \int \frac{d^3p_\xi}{(2\pi)^3} \frac{d^3p_\eta}{(2\pi)^3} \chi_M(p_\xi, p_\eta)$
which then fulfills the Salpeter equation:

\[
(H\Phi_M)(\vec{p}_\xi, \vec{p}_\eta) = \sum_{i=1}^{3} H_i \Phi_M(\vec{p}_\xi, \vec{p}_\eta) \\
+ \left( \Lambda_1^+ \otimes \Lambda_2^+ \otimes \Lambda_3^+ + \Lambda_1^- \otimes \Lambda_2^- \otimes \Lambda_3^- \right) \gamma^0 \otimes \gamma^0 \otimes \gamma^0 \int \frac{d^3p'_\xi}{(2\pi)^3} \frac{d^3p'_\eta}{(2\pi)^3} V^{(3)}(\vec{p}_\xi, \vec{p}_\eta, \vec{p}'_\xi, \vec{p}'_\eta) \Phi_M(\vec{p}'_\xi, \vec{p}'_\eta) \\
+ \left( \Lambda_1^+ \otimes \Lambda_2^+ \otimes \Lambda_3^- - \Lambda_1^- \otimes \Lambda_2^- \otimes \Lambda_3^+ \right) \gamma^0 \otimes \gamma^0 \otimes I \int \frac{d^3p'_\xi}{(2\pi)^3} \left[ V^{(2)}(\vec{p}_\xi, \vec{p}'_\xi) \otimes I \right] \Phi_M(\vec{p}'_\xi, \vec{p}_\eta) \\
+ \text{cycl. perm. (123)}.
\] (2)

Again, if one would drop all terms involving the negative energy projectors \(\Lambda^-\) one arrives at a Schrödinger-type equation with relativistic corrections. Although the full Salpeter hamiltonian (2) is not positive definite with respect to the scalar product of the Salpeter amplitudes and thus positive and negative energy solutions occur, the negative energy solutions can (via the CPT-transformation) be mapped to positive energy solutions of opposite parity and consequently this approach leads to the same number of states as the non-relativistic quark model. Again, adopting a linear three-body confinement potential with a suitable spin dependence avoiding large spin-orbit splittings and the instanton-induced interaction to account for the major spin-dependent splittings with only seven parameters an excellent description has been obtained for all light-flavoured baryons, see [8, 9], including selective parity doubling and the Regge-trajectories up to the highest measured masses and total angular momenta. In [3] the results for \(N\)- and

**FIGURE 3.** Low lying \(N\)- (left) and \(\Delta\)-resonances (right). In each column from left to right the calculated result from the relativized quark model with a OGE-based quark interaction [4], the experimental data, the result from the instantaneous Bethe-Salpeter Equation with instanton-induced interactions and the results from a quark model calculation with Goldstone boson exchange [2] is displayed.

\(\Delta\)-resonances of low-mass and low angular momenta is compared to experimental data
as well as to the results from the relativized constituent quark model using parts of the OGE as a residual interaction, see [4] and the results from a constituent quark model developed by the Graz-group, which employs (flavour dependent) modified Yukawa-type potentials based on Goldstone-Boson-Exchange, see e.g. [2]. The latter treatment has the obviously satisfactory feature to be able to reproduce the first excited states of positive parity below the negative parity states, whereas the other treatments do yield a low lying Roper-like resonance but slightly above the lowest negative parity states. All calculations can not account for some negative parity \( \Delta \)-resonances at approximately 1.9 GeV, see also the contribution of Ch. Weinheimer to this conference.

As for the mesons, in the Bethe-Salpeter approach electroweak currents can be calculated covariantly and (in lowest order) parameter free within the Mandelstam formalism [10]. The results for the magnetic moments of octet and decuplet baryons are given in Table 3 together with experimental data and the results which the Graz-group obtained employing the point-form of Dirac’s relativistic quantum mechanics. Although the calculational frameworks and the quark dynamics differ substantially in both approaches the results are remarkably similar and stress the importance of a relativistically covariant calculation of electromagnetic currents. This holds a fortiori for the calculation of electromagnetic (transition) form factors, see e.g. the comparison in Fig. 4. For more results on electroweak transition form factors we refer to [10]. Some new, representative results for semi-leptonic decays, calculated from the weak baryonic currents in the Mandelstam formalism, are listed in Table 4. Electroweak currents, provided that they are calculated in a relativistically covariant framework, can thus be satisfactory calculated in lowest order.

This is no longer holds a priori for the calculation of strong two-body decays, where channel couplings and mixing can be important, and in principle resonances could be even generated dynamically through such effects. Nevertheless it seems interesting to investigate to what extent a lowest order calculation, without any introduction of new parameters can describe some experimental features.

In the framework of the Mandelstam formalism the amplitude for the strong mesonic decay of excited baryons can be obtained in lowest order by evaluating the simple quark loop diagram displayed on the left, which involves the vertex functions (amputated Bethe-Salpeter-amplitudes) of the participating meson, obtained from the calculation on mesons [6], and of the initial and final baryon.
FIGURE 4. Comparison of the form factors calculated in the point-from approach in the constituent quark model with Goldstone Boson Exchange (GBE) of [2] and in the Mandelstam formalism on the basis of the Bethe-Salpeter Equation (BSE) [10] with experimental data; Left: Magnetic form factor of the proton; middle: Magnetic form factor of the neutron and right: axial form factor (adapted from [2]).

TABLE 4. Decay rates and axial vector couplings of semi-leptonic decays of baryons.

| Decay | $\Gamma$ [$10^6$ s$^{-1}$] | $gf_A/gf_V$ |
|-------|-----------------------------|-------------|
|       | Exp. | Calc. | Exp. | Calc. |
| $n \to pe^{-}\bar{\nu}e$ | $3.16 \pm 0.06$ | $6.9 \pm 0.2$ | $0.93 \pm 0.14$ | $0.5 \pm 0.1$ | $3.3 \pm 0.2$ | $68 \pm 34$ | $0.60 \pm 0.13$ | $3.04 \pm 0.27$ | $2.1 \pm 1.3$ | $1.2670 \pm 0.0035$ | $1.21$ | $-0.718 \pm 0.015$ | $-0.82$ | $0.340 \pm 0.017$ | $0.25$ | $1.32^{+0.21}_{-0.17} \pm 0.05$ | $1.38$ | $-0.25 \pm 0.05$ | $-0.27$ | $1.60$ | $1.04$ |

Although in general the calculated partial widths are too small to account for the experimental values quantitatively, appreciable decay widths are found only for the well established resonances, the predicted values for higher lying resonances being in general smaller by at least an order of magnitude, see also Fig. 5, explaining why these have not been observed so far in elastic pion-nucleon scattering. This observation is in accordance with previous findings cited in [11, 4]. In Table 5 the calculated...
**FIGURE 5.** Decay amplitudes (proportional to the square root of the partial decay width) of strong $N^* \to N\pi$ decays. In each column (i.e. for each spin and parity $J\pi$) the experimental value (thin horizontal bars at the experimental resonance position) is compared to the calculated value (thick horizontal bars at the calculated resonance position).

Partial decay widths of some selected low lying $N$- and $\Delta$-resonances are compared to experimental data and recent results from the Graz group with a relativistic elementary meson emission [2] (with no extra parameters) as well as the results from the relativized quark model invoking the $^3P_0$-model [11].

**TABLE 5.** Partial decay widths in MeV of some strong two-body decays of $N$- and $\Delta$-resonances.

| Decay          | BSE | GBE | $^3P_0$ | Exp.  | Decay          | BSE | $^3P_0$ | Exp.  |
|----------------|-----|-----|--------|-------|----------------|-----|--------|-------|
| $S_{11}(1535) \to N\pi$ | 33  | 93  | 216    | $(68 \pm 15)^{+45}_{-50}$ | $\to \Delta\pi$ | 1   | 2      | < 2   |
| $S_{11}(1650) \to N\pi$ | 3   | 29  | 149    | $(109 \pm 26)^{+4}_{-5}$  | $\to \Delta\pi$ | 5   | 13     | $(6 \pm 5)^{+2}_{-0}$ |
| $D_{13}(1520) \to N\pi$ | 38  | 17  | 74     | $(66 \pm 6)^{-5}_{-8}$   | $\to \Delta\pi$ | 35  | 35     | $(24 \pm 6)^{+3}_{-2}$ |
| $D_{13}(1700) \to N\pi$ | 0.1 | 1   | 34     | $(10 \pm 5)^{+5}_{-3}$   | $\to \Delta\pi$ | 88  | 778    | seen  |
| $D_{15}(1675) \to N\pi$ | 4   | 6   | 28     | $(68 \pm 7)^{+14}_{-5}$  | $\to \Delta\pi$ | 30  | 32     | $(83 \pm 7)^{+17}_{-6}$ |
| $P_{11}(1440) \to N\pi$ | 38  | 30  | 412    | $(228 \pm 18)^{+65}_{-65}$ | $\to \Delta\pi$ | 35  | 11     | $(88 \pm 18)^{+28}_{-25}$ |
| $P_{33}(1232) \to N\pi$ | 62  | 34  | 108    | $(119 \pm 0)^{+5}_{-5}$  | $\to \Delta\pi$ | 72  | 18     | $(68 \pm 23)^{+14}_{-14}$ |
| $S_{31}(1620) \to N\pi$ | 4   | 10  | 26     | $(38 \pm 7)^{+8}_{-8}$   | $\to \Delta\pi$ | 72  | 18     | $(68 \pm 23)^{+14}_{-14}$ |
| $D_{13}(1700) \to N\pi$ | 2   | 3   | 24     | $(45 \pm 15)^{+15}_{-15}$| $\to \Delta\pi$ | 52  | 262    | $(135 \pm 45)^{+45}_{-45}$ |
CONCLUSION

In conclusion we think that we have demonstrated, that constituent quark models provide a very useful tool in understanding hadron properties in a unified way: This not only involves a description of the mere mass spectrum, but also numerous decay amplitudes and electroweak (transition) form factors. In particular the field theoretical approaches which rely on the description of bound states of quarks through coupled Bethe-Salpeter/ Dyson-Schwinger equations have provided very interesting results, unfortunately so far only for the ground states and some low-lying excited states. In this respect the approach based on the instantaneous Bethe-Salpeter equation, using free-form fermion propagators with constituent masses, implementing confinement by a string-like linearly rising potential and with instanton-induced interactions to explain the spin-dependent mass splittings seems to be a very efficient compromise combining the advantages of a relativistically covariant field theoretical treatment with the successful concepts of the (non-relativistic) constituent quark model. Adopting the point form of Dirac’s Relativistic Quantum Mechanics does improve the description of observables within the latter category drastically, and supports the main findings of our treatment that a relativistic treatment of decay amplitudes, especially for processes at higher momentum transfers is absolutely imperative.

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