Baryon resonances and strong decays

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Abstract. Constituent quark models provide a reasonable description of the baryon mass spectra. However, even in the light- and strange-flavor sectors several intriguing shortcomings remain. Especially with regard to strong decays of baryon resonances no consistent picture has so far emerged, and the existing experimental data cannot be explained in a satisfactory manner. Recently first covariant calculations with modern constituent quark models have become available for all \(\pi\), \(\eta\), and \(K\) decay modes of the low-lying light and strange baryons. They generally produced a remarkable underestimation of the experimental data for partial decay widths. We summarize the main results and discuss their impact on the classification of baryon resonances into flavor multiplets. These findings are of particular relevance for future efforts in the experimental investigation of baryon resonances.

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1 Introduction

Modern constituent quark models (CQMs) have reached an improved description of the light and strange baryon spectra. Especially the masses of ground and resonance states below about 2 GeV can generally be reproduced in a reasonable manner\cite{1}. However, there are also some cases where disturbing discrepancies remain. A notable example is the \(\Lambda(1405)\) resonance, which cannot be explained by any CQM, relying only on three-quark configurations. In addition there are considerable uncertainties above all in the \(\Sigma\) and \(\Xi\) excitation spectra due to a limited experimental data base.

Regarding strong decays of light and strange baryon resonances no satisfactory description has yet been reached. So far, the mostly nonrelativistic CQM calculations have produced results for partial decay widths that scatter around the experimental data\cite{2,3,4,5,6}. In particular, it has proven difficult to explain some theoretical decay widths that grossly overestimate the measured ones. Sometimes ad-hoc parametrizations (leading beyond the CQMs) have been introduced in order to fit the data, but a consistent picture has not emerged.

Recently, we performed covariant calculations of the \(\pi\), \(\eta\), and \(K\) decay widths employing relativistic CQMs within the so-called point-form spectator model (PFSM)\cite{7,8,9}. The direct predictions for partial decay widths produced a completely different pattern. The relativistic results systematically underestimate the experimental data. Nevertheless it became evident that relativity plays an immense role. In particular it could be shown that a nonrelativistic reduction causes large effects. They mainly result from truncations in the spin-coupling terms and the neglect of Lorentz boosts thus explaining the variations in the nonrelativistic calculations. Similar results for relativistic decay widths have been obtained by the Bonn group using an instanton-induced CQM in the framework of the Bethe-Salpeter equation\cite{10,11}.

Even though the relativistic decay calculations do not yet provide a satisfactory explanation of the experimental decay widths, they produce a systematic pattern of the results, which allows one to investigate existing ambiguities in the classification of baryons into flavor multiplets. In the following we detail some of the corresponding implications with regard to hyperon resonances.

2 Systematics of strong decays

From the comprehensive relativistic studies of \(\pi\), \(\eta\), and \(K\) decay widths\cite{7,8,9} a classification of light and strange baryon resonances into \(SU(3)\) flavor multiplets is suggested as given in Tables 1 and 2. While in most instances the octet and decuplet assignments agree with the ones by the PDG\cite{12}, there occur also some differences. The \(\Lambda(1810)\) is interpreted as flavor singlet, not as octet, and the \(\Sigma(1620)\) falls into the octet involving the \(N(1650)\). In addition, the \(\Xi(1690)\) is assigned to the octet involving \(N(1440)\), \(\Sigma(1560)\) falls into the octet involving \(N(1535)\), the \(\Sigma(1940)\) is assigned to the octet involving \(N(1700)\), and the \(\Xi(1690)\) as well as \(\Xi(1950)\) are members of the octets involving \(N(1440)\) and \(N(1675)\), respectively. Except for the \(\Lambda(1810)\) similar findings have also been obtained by Guzey and Polyakov\cite{13}. However, we remark that the \(\Lambda(1810)\) is also identified as a flavor singlet by Matagne and Stancu\cite{14}. In the context of our
produce three lower-lying eigenstates. From experiments there are only a few exceptions: The partial widths of theoretically underestimate the experiments by similar amounts. This naturally of the experimental data. It is immediately evident that in each one of the octets, denoted after the contained nucleon member, the theoretical widths systematically underestimate the experiments by similar amounts. There are only a few exceptions: The partial widths of $\Lambda(1670) \to \Sigma\pi$ and $\Lambda(1690) \to \Sigma\pi$ come out too large; this can be explained by the large admixtures of flavour singlet contributions in each case (see Table 1). Also the $N(1710) \to N\pi$ decay width appears to be unusually large; the reason is not yet particularly clear, and it might be caused by a deficiency in the theory and/or experiment (disagreeing partial wave analyses). A further exception to underestimated widths consists in the $N(1650) \to N\eta$ decay, which represents a notorious difficulty for CQMs. The remaining results in the $\eta$ channel should not be taken too seriously as the corresponding phenomenological partial decay widths are basically zero.

Of particular interest in the study of decay widths is the $J^P = \frac{3}{2}^-$ sector of the $\Sigma$ resonances. Here, the CQMs produce three lower-lying eigenstates. From experiments only one established resonance (with at least three-star) is reported, namely, the $\Sigma(1750)$. Its partial width for the decay into $\Sigma\pi$ is quoted as being less than $8\%$ of the total width, i.e. it should be rather small $\Sigma(1750)$. Now, the PDG also gives two more $\Sigma$ resonances lying below the $\Sigma(1750)$, however, only with two-star status. They are the $\Sigma(1620)$, whose $J^P$ is determined to be $\frac{1}{2}^-$, and the $\Sigma(1560)$ without definite $J^P$ assignment. If one interprets the two lower mass eigenstates as the $\Sigma(1560)$ and the $\Sigma(1620)$ and the third eigenstate as the $\Sigma(1750)$, then a consistent pattern of the partial decay widths is achieved. This naturally leads to the assignments of the $\Sigma(1560)$ and the $\Sigma(1620)$ to the flavor octets as given in Table 1. As a consequence the third eigenstate, $\Sigma(1750)$, falls into the decuplet (cf. Table 2). This classification is supported also by a more detailed investigation of baryon resonance wave functions considering their specific spin-, flavor- and spatial structures as resulting from relativistic CQMs.

| $\Lambda(1670)$ |
|-----------------|
| $\Xi(1385)$ |
| $\Xi(1530)$ |
| $\Omega(1672)$ |
| $\Sigma(1650)$ |
| $\Sigma(1690)$ |
| $\Sigma(1750)$ |

Table 2. Classification of flavor decuplet baryons. The superscripts denote the percentages of decuplet content in the mass eigenstates as calculated with the GBE CQM [15].

3 Conclusions and outlook

Recent relativistic results for strong decay widths of baryon resonances have produced a completely different pattern of CQM predictions. The magnitudes of the various partial decay widths are generally too small and not compatible with phenomenology. We have considered the direct predictions of CQMs without any additional fitting of the results. The findings obtained within the PFSM approach [17,18] are surprisingly similar to the ones in the framework of the Bethe-Salpeter equation [19,20]. The defects hint to missing contributions. One must bear in mind that the baryon ground and resonance states are all described as bound three-quark eigenstates of the invariant mass operator. Thus they have zero widths and cannot decay. The decay amplitudes are merely calculated as transition matrix elements between bound states. Consequently the shortcomings are not really surprising. Fitting the results a-posteriori to the experimental data will not help in understanding the strong decays. Rather one should think of improvements in the description of resonance states and the decay operator.

The PFSM provides the simplest relativistic decay mechanism. It reduces to the elementary emission model in the nonrelativistic limit [8]. However, it is not a mere one-body operator but effectively includes many-body contributions [16,17]. Certainly the point-form calculation is manifestly covariant and contains all relativistic effects according to the spectator-model construction. Additional studies along this line, employing different quark-meson couplings, could provide further insights. Ultimately, however, improvements of the decay operator might be necessary that go beyond the spectator model.

Another step towards improvements consists in an extension of CQMs to include explicit couplings to the decay channels. In such a framework, the baryon states will receive a finite width leading to a more realistic description of the excited resonances. Of course, such a procedure will
not only have an effect on the widths, but also modify the (real) mass values (cf., e.g., refs. [18,19]). As a result a complete reconstruction of the CQMs will be necessary and the interpretation of the theoretical baryon spectra might then appear in a different light.

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