Signals of Quark Substructure in Hadron Reactions at Intermediate Energies

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Abstract

Exotic hadrons of a few GeV/$c^2$ mass, exhibiting a spectrum determined by the perturbative interaction of a non-minimal number of valence quarks, have long been predicted as signals of the underlying QCD structure. Realistic models must include short range (asymptotic freedom) and long range (confinement) effects of QCD. Models that adequately include the confinement region predict exotic masses 0.2–0.8 GeV higher than the others. The R-matrix hybrid model has made the most detailed predictions, some of which have been experimentally observed. This model postulates a short range valence quark and perturbative gluon exchange region, connected to a long-range hadronic region by an R-matrix boundary condition. In this presentation we will give a brief introduction to the model and then review the status of its predictions and new applications:

New Ann ($90^\circ$) data in $pp$ elastic scattering corroborates earlier evidence for the lowest mass $I = 1$ state, $^1S_0$ (2.7 GeV/$c^2$). The lowest predicted $I = 0$ di-nucleon, $^3S_1$ (2.63 GeV/$c^2$), is consistent with recent $\Delta \sigma_L(np)$ in that energy region. Predictions are made for several other observable di-nucleons with $< 3.0$ GeV/$c^2$ mass.

The $S = -2$ di-hyperon sector has long been of interest. Searches for a bound state (as predicted by some models) have been negative. The R-matrix calculation predicts a higher mass $\Lambda\Lambda-\Xi N$ resonance at 2.35 GeV/$c^2$. Specific predictions for the observables in $\Xi N$ scattering are being made.

Spectra for the $\Lambda N-\Sigma N$ and the $KN$ exotics have been predicted. There is insufficient data at exotic energies, but the model fits the low energy data well.

Work in progress indicates that the $d^*$ (a quasi-bound $\Delta-\Delta$) predicted in a different model is inconsistent with $np(3D_3)$ scattering data. A model of the recently observed $d'(2065)$ as a deeply bound $N-S_{11}(1S_0)$ is being constructed.
1 Introduction

At very high momentum transfers, where short range effects dominate, the asymptotic freedom property of QCD correctly predicts that perturbative quark/gluon processes will dominate particle reaction observations. Therefore experiments at high energies have been able to identify the SU(3) color structure, charges and masses of quarks and gluons and the three families of quarks and leptons, among other properties of QCD. The other main property expected of QCD, confinement, can be inferred from the absence of free quarks and gluons in high energy reactions. However the specific nature of confinement and the transition to asymptotic freedom can not be learned from these experiments. At low energies we expect, and have overwhelming experimental confirmation, that confinement of quarks into hadrons is dominant, leading to an effective field theory of hadrons interacting via exchange of hadrons. At short distances between hadrons one again expects quark and gluon degrees of freedom to be in evidence, but the details of this short range structure can not be unfolded in the restricted momentum-transfer range at low energies. Only one parameter, the range of the core, can be determined. However the low energy property of this core (it excludes almost all of the wave function from the inner region) has many possible explanations other than QCD.

But at intermediate energies there is an opportunity to learn more about confinement and its transition to asymptotic freedom. Not only do the higher momentum transfers possible allow a finer-grained study of the interior region, but, in reaching energies corresponding to quark states confined to the interior, resonance conditions are achieved which enable substantial penetration of the wave function to the interior. These resonances carry much information concerning the perturbative QCD behavior of the multi-quark configurations (such as cavity corrections to masses) and about the transition mechanism to confinement (through the width of decay to the simple hadron components of the multi-quark configuration). Resonances of this type are often called “exotic”. Most of these resonances can be expected to occur at high enough excitations so that they are very inelastic and in a background of many partial waves. This will make them difficult to observe, but, as we will see, possible to identify by precise measurement of certain spin observables. It is possible that some exotic resonances (with several heavier quarks in the configuration) may be of low excitation energy or even bound. We shall discuss the doubly-strange dibaryon case which is the best such prospect including only u, d, and s quarks.

Exotic hadrons of a few GeV/c^2 mass have long been predicted as signals of the underlying QCD structure. The term “exotic” refers to bound states or resonances which are (i) constructed from more quarks than the minimal color singlet quark configurations (q^3, q̄q), of the ordinary hadrons, and (ii) not dominantly a “molecular” system of quarks already clustered into the normal hadrons, interacting via hadron exchange. Exotics would be characterized by a spectrum similar to that of the perturbative spectrum of a non-minimal number of valence quarks.
A realistic model must enable a dynamic interaction of the exotic (asymptotic freedom) and molecular (confinement) effects. Models that adequately include the confinement region \[1, 2, 3, 4, 5\] predict masses 0.2–0.8 GeV higher than those that do not \[6, 7, 8, 9\]. The R-matrix hybrid model \[1, 2, 3, 10\] has made the most detailed predictions, some of which have been experimentally observed. This model postulates a short range valence quark and perturbative gluon exchange region, connected to a long-range hadronic region by an R-matrix boundary condition of the form

\[
r_0 \frac{d\psi^{W}_\alpha}{dr_0} = \sum_{\beta} f_{\alpha\beta}(W) \psi^{W}_\beta(r)
\]  

where \(\psi\) is the 2-hadron external wave function and \(f_{\alpha\beta}(W)\) is a meromorphic function, with real poles of positive residue

\[
f_{\alpha\beta}(W) = f_{\alpha\beta}^0 + \sum_{i} \frac{\rho_{\alpha\beta}^i}{W - W_i}
\]
with

$$\rho_{\alpha\beta}^i = -r_0 \frac{\partial W_i}{\partial r_0} \xi_{\alpha}^i \xi_{\beta}^i$$  (3)

where $W_i$ is the energy of an internal quark state that vanishes at $r_0$, $i$ running over the complete set with the given quantum numbers, and the $\xi_{\alpha}^i$ are the fractional parentage coefficients (fpc’s) of the quark configuration $i$ with the hadron channel $\alpha$. The separation radius $r_0$ corresponds to a distance between the hadron centers-of-mass of $\sim 1$ fm, which must satisfy the R-matrix method condition that the interior description, perturbative QCD in this case, is a good approximation at this radius, while simultaneously enabling a fit to the data below the first exotic. These conditions are satisfied by the parameters of the Cloudy Bag Model, but not by those of the MIT Bag Model [1, 2]. This an example of the greater constraint of hadron reactions on QCD models, compared to that of single hadron properties. We display the fit to the low energy polarized and unpolarized differential pp cross sections, see Fig. 1.

It is important to note that the multi-quark configurations overlap not only with hadron pairs, but also with colored pairs of quark subsets. Therefore the sum of the squares of the fpc’s in (3) is less than unity. For the case of six S-state quarks (of whatever flavor) the sum is 0.2. The result of this ”hidden color” is that the resonance widths are only a fraction of the approximately $r_0^{-1}$ expected if the system simply ”fell apart”. This results in widths of the order of 50 MeV, which are discernible against the slowly varying background, and yet are easily resolved in medium energy experiments.

In the following sections we will review the status of several of the R-matrix model’s predictions.

2 Nucleon-Nucleon Sector: Exotics and Observables

Two-baryon systems have six valence quarks and consequently only non-minimal quark configurations. In the perturbative limit assumed for exotics, the lowest mass configurations are the $[q(1s_{1/2})]^6$ even parity and the $[q(1s_{1/2})]^5q(1p_{1/2,3/2})$ odd parity cases, with q either u or d for nucleons.

The lowest mass $I = 1$ di-nucleon state, a $^1S_0$, which is predicted [1, 2] to be at 2.7 GeV/c$^2$, has been observed in Ann ($90^\circ$) of pp elastic scattering [11], see Fig. 2, as well as observed [12] in $\Delta \sigma_L (pp)$.

The lowest mass $I = 0$ di-nucleon [1], a $^3S_1$ at (2.63 GeV/c$^2$), is consistent with recent $\Delta \sigma_L (np)$ data [13] in that energy region. There is also evidence from $A_y$ in pp $\rightarrow d\pi^+$ [14] for an $I = 1$, spin triplet di-nucleon near 2.8 GeV/c$^2$) mass. Predictions are made for several other observable di-nucleons with $\leq 3.0$ GeV/c$^2$ mass [15], such as the lowest mass odd parity $^3P_1$ resonant structure, Fig. 3, of about 70 MeV width.
Figure 2: $A_{nn}(pp)$ at 90°: The data is that of the SAID \cite{17} database and from the 1997 thesis of C. Allgower \cite{11}, a preliminary analysis of 1993–95 Saturne II data (systematic errors included). The dashed curve is from the SAID PSA \cite{17} which did not include the Allgower data. The solid curve adds the $^1S_0$ resonance of the 1995 R-matrix model to the SAID PSA. The position of the resonance has been decreased by 20 MeV from the prediction of Ref. \cite{2}.

Figure 3: $^3P_1$ Exotic Resonance: The pp($^3P_1$) $\text{Im(amp)} = \frac{1}{2}(1 - \eta \cos 2\delta)$ predicted by the f-pole of the \[q(^1S_{1/2})]q(^1P_{\frac{1}{2}}]\ configuration \cite{15}. The c.m. width is 80 MeV.
3 Di-hyperon Sector

The $S = -2$ di-hyperon sector has long been of interest because of an early prediction of a bound di-lambda (H particle) \([9]\). The R-matrix calculation differs, predicting a higher mass $\Lambda\Lambda - \Xi N$ resonance at $2.35 \text{ GeV}/c^2$ \([3]\). Searches for the bound state have been negative \([10]\), leaving the possibility that the predicted resonance exists. In fact the exotic in question, a $\text{dimF}=1$, $[q(1s_{1/2})]^4s(1s_{1/2})$ quark configuration, overlaps more strongly with the $\Xi N$ and $\Sigma\Sigma$ channels than with the $\Lambda\Lambda$ channel. Because the exotic resonance is predicted to be above the $\Xi N$ threshold, the effect of the resonance should be substantial in $\Xi N$ scattering, a process observable in the laboratory. We are constructing a coupled channel R-matrix model for these channels so that specific predictions can be made for $\Xi N$ scattering, to separate the effects of the $\Lambda\Lambda$ and $\Sigma\Sigma$ thresholds from that of the exotic resonance.

4 Nucleon–Hyperon and Kaon–Nucleon Sectors

Spectra for the $\Lambda N - \Sigma N$ and the $KN$ exotics of the $[q(1s_{1/2})]^5s(1s_{1/2})$ and the $[q(1s_{1/2})]^4\bar{s}$ configurations have been predicted \([3, 10]\). The rich exotic nucleon-hyperon spectrum predicted, together with the relevant thresholds, is shown in Fig. 4. Modern data is not available in the predicted resonance region, but the R-matrix model can be compared with

![Figure 4: Nucleon-Hyperon Exotic Spectrum](image)

**Figure 4:** *Nucleon-Hyperon Exotic Spectrum:* The R-matrix model predictions for the exotics produced produced by the $[q(1s_{1/2})]^6s(1s_{1/2})$ quark configurations \([10]\). The channel thresholds are shown by dashed lines (ground state baryons) and dotted lines (isobar + ground state).
lower energy nucleon-hyperon reaction data to which it is a good fit [10]. As an example we show the total cross sections for Λ-N elastic scattering and Σ-N production, Fig. 5, clearly demonstrating the effect of the Σ-N threshold on the elastic Λ-N prediction, also reflected in the data.

![Figure 5: Λ-N Reactions](image)

There are hints of structure in old bubble chamber data for the KN system.

## 5 Is there a d*?

In a cluster model which screens the interaction between quarks in different baryons [7] a quasi-bound I=0, $^7S_3$ Δ-Δ state of mass near 2.1 GeV/c$^2$ is predicted, but has not yet been observed. This channel is coupled to the np($^3D_3$-$^3G_3$) channel by long range tensor potentials arising from pi- and rho-meson exchange. It is therefore expected to have a substantial decay width to that channel. In np scattering this would show up as a resonance of equal or greater width at a neutron beam energy $T_{\text{lab}} = 425-550$ MeV. For $T_{\text{lab}} \leq 800$ MeV there are over-complete sets of precise spin observables at several energies, in particular at 142, 210, 325, 425, 515, 650 and 800 MeV. The phase shift analyses [17, 18] are able to determine the $^3D_3$-$^3G_3$ phase angles to 0.4 deg. or better, and produce a smooth energy dependence within that error. A resonance, elastic in this energy region, needs to have a width of $\leq 1$ MeV to reproduce that degree of smoothness.

The R-matrix model with all relevant $I = 0, 3^+$ channels fits the data well, when there
is no $d^*$. It can produce a quasi-bound $^7S_3$ $\Delta$-$\Delta$ state half way between 425 and 515 MeV by adjusting the energy-independent term of that channel’s f-matrix component. Furthermore it can minimize the width induced by meson exchanges by adjusting the off-diagonal constant f-matrix component. The resultant width is 4 MeV, too large to agree with the phase shift analyses as seen in Fig. 6. There is a greater energy gap between the well determined phases at $T(\text{lab})$ of 650 and 800 MeV, but the larger np phase space increases the resonance width.

Figure 6: $d^*$ Resonance in np($^3D_3$-$^3G_3$): The coupled channel R-matrix model is able to predict the effect of a $\Delta$-$\Delta(\ ^7S_3\ )$ bound state on the np elastic scattering parameters. The bound state is induced in the region predicted in Ref. [7] and its width minimized by adjustment of the f-matrix as described in the text. The fit to the PSA of Refs. [17] and [18] is very poor near resonance, especially for $\delta(^3D_3)$. The best fit of the R-matrix model without a $\Delta$-$\Delta$ bound state (not shown) is very good.
6 What is the d’?

There is considerable evidence indicating a narrow dibaryon resonance at 2.065 GeV, probably in an I=0 state \cite{19}. It is conjectured to be in a 0^- state to prevent it from having a large decay width to an NN channel. This d’ may be a bound \pi NN system \cite{20}. The corresponding exotic configuration is more than 0.5 GeV too massive in the R-matrix model as well as in a constituent quark model calculation \cite{21}. Another possibility is that it could be a N-S_{11} system bound in an S-wave by the effect of the constant term in the f-matrix. We will explore this with the R-matrix model, which can predict its electromagnetic decay widths.

7 Conclusions

The R-matrix model of strong interactions incorporates both the long range and short range properties of QCD permitting the description of two-hadron interactions that include aspects of both asymptotic freedom and confinement. In particular predictions can be made for the spectra of exotic resonances, while also describing the properties of molecular (or mixed) resonances and the details of the background reactions. This enables a better determination of non-perturbative properties of QCD than obtainable from single hadron properties alone. The experimental discovery of more of the exotic spectrum would greatly refine our knowledge of QCD dynamics.

The R-matrix model assumes a sudden transition from perturbative QCD to the region of hadron exchange forces. We are considering the possible introduction of the chiral symmetric hadron phase between \( r_0 \) (corresponding to the deconfinement transition) and the broken symmetry asymptotic hadron region.

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