SONIFICATION OF QUANTUM SPECTRA

Alberto de Campo, Christopher Frauenberger, Robert Höldrich

Institute of Electronic Music and Acoustics IEM
University for Music and Dramatic Arts, Graz,
{decampo, frauenberger, hoeldrich} @iem.at

Thomas Melde, Willibald Plessas, Bianka Sengl

Theoretical Physics / Institute of Physics
University of Graz, Graz, Austria
{ thomas.melde, willibald.plessas, bianka.sengl } @uni-graz.at

ABSTRACT

Quantum spectra provide an interesting field for auditory display due to the richness of their data sets. Here, we are concerned with the sonification of quantum-mechanical spectra of baryons, the most fundamental particles of subatomic physics observed in nature. The data under investigation stem from different competing theoretical models designed for the description of baryon properties. We report on first attempts towards finding valid and useful strategies for displaying, comparing and exploring various model predictions in relation to experimentally measured data by means of sonification. The aim is to investigate the possibilities of sonification in order to develop them as a tool for classifying and explaining baryon properties in the context of present particle theory.

1. INTRODUCTION

The investigation of quantum spectra plays an important role in many areas of modern physics. It is essential to understand the structure and interactions of composite systems in such fields as condensed-matter, molecular, atomic, and subatomic physics. In the present work we specifically deal with baryons, the fundamental building blocks of matter directly observed in experiments. Baryons – most prominently among them the proton and the neutron – are considered as bound systems of three quarks, which are presently known as the ultimate constituents. The forces governing their properties and behaviour are described within the theory of quantum chromodynamics (QCD). While up to now this theory is not yet exactly solvable for baryons (at low and intermediate energies), one resorts to effective models, such as the constituent quark model (CQM).

CQMs have been suggested in different variants. Existing models are distinct mainly with respect to their input for the forces binding the constituent quarks. As a result one is left with a variety of quantum-mechanical spectra for the ground and excited states of baryons. The characteristics of the spectra contain a wealth of information important for the understanding of baryon properties and interactions. This makes baryon spectra an extremely interesting field for sonification studies.

The present investigation is part of the new interdisciplinary research project 'SonEnvir' [1], in which sonification experts work together with scientists from four interdisciplinary domains (physics, neurology, sociology, and signal processing) in order to develop a sonification environment for general application in different areas of data analysis and exploration.

1. CONSTITUENT QUARK MODELS

The concept of constituent quarks was introduced already quite some time ago by Gell-Mann [2] and Zweig [3], based on symmetry considerations in the classification of hadrons, the strongly interacting elementary particles. The first CQMs for the description of hadron spectra were introduced in the early 1970's [4]. The original naïve CQMs relied on simple models for the confinement of constituent quarks (such as the harmonic oscillator potential) and employed rudimentary hyperfine interactions. Furthermore they were set up in a completely nonrelativistic framework. In the meantime CQMs have undergone a vivid development. Over the years more and more notions deriving from QCD have been implemented, and CQMs are constructed along a relativistic formalism.

Modern CQMs all use a confinement potential of linear form, as suggested by QCD. For the hyperfine interaction of the constituent quarks several competing dynamical concepts are put forward. A prominent representative is the one-gluon-exchange (OGE) CQM, whose dynamics for the hyperfine interaction basically relies on the original ideas of de Rújula et al. [4]: the effective interaction between the constituent quarks is generated by the exchange of a single gluon. Here we consider a relativistic variant of the OGE CQM as constructed by Theußl et al. [5]. A different approach is followed by the so-called instanton-induced (II) CQM [6], whose hyperfine forces derive from the 't Hooft interaction. Several years ago the Graz group has suggested a hyperfine interaction based on the exchange of Goldstone bosons. This type of dynamics is motivated by the spontaneous breaking of chiral symmetry (SBχS), which is an essential property of QCD at low energies. The SBχS is considered to be responsible for the quarks to acquire a (heavier) dynamical mass, and their interaction should then be generated by the exchange of Goldstone bosons, the latter being another consequence of SBχS. The Goldstone-boson-exchange (GBE) CQM was originally suggested in a simplified version, based on the exchange of pseudoscalar bosons only [7]. In the meantime an extended version is also available [8].

1. QUANTUM-MECHANICAL SOLUTION OF CONSTITUENT QUARK MODELS

Modern CQMs are constructed in the framework of relativistic quantum mechanics (RQM). They are characterised by a Hamiltonian operator H that represents the total energy of the system under consideration. For baryons, which are considered as bound states of three constituent quarks, the corresponding Hamiltonian reads

$$H = H_0 + \sum_{i<j}^{3} [V_{conf}(i,j) + V_{hf}(i,j)] \qquad (1)$$

The first term on the right-hand side denotes the relativistic kinetic energy of the system (of the three constituent quarks), and the sum includes all mutual quark-quark interactions. It consists of two parts, the confinement potential V_{conf} and the hyperfine interaction V_{hf}. The confinement potential prevents the constituent quarks from escaping the volume of the baryon (being of the order of 10^{-15} m); no free quarks have ever been observed in nature. The hyperfine potential provides for the fine structure of the energy levels in the baryon spectra. Different dynamical models lead to distinct features in the excitation spectra of baryons.

In order to produce the baryon spectra of the CQMs one has to solve the eigenvalue problem of the Hamiltonian in eq. (1). Several methods are available to achieve solutions to any desired accuracy. The Graz group has applied both integral-equation [9] as well as differential-equation techniques [10].

Upon solving the eigenvalue problem of the Hamiltonian one ends up with the eigenvalues (energy levels) and eigenstates (quantum-mechanical wave functions) of the baryons. They are characterised according to the conserved quantum numbers, the total angular momentum J (which is half integer in the case of baryons) and the parity P (being positive or negative). The different baryons are distinguished due to their flavor content u, d, and s (for 'up', 'down', and 'strange'). For example, the proton is uud, the neutron is udd, the Δ^{++} is uuu, and the Λ^0 is uds.

2. CLASSIFICATION OF BARYONS

The total baryon wave function Ψ_{XSFC} is composed of spatial (X), spin (S), flavor (F), and color (C) degrees of freedom corresponding to the product of symmetry spaces

$$O(3)_R \otimes SU(2)_S \otimes SU(3)_F \otimes SU(3)_C \qquad (2)$$

It is antisymmetric under the exchange of any two particles, since baryons must obey Fermi statistics.

2.1. Color

The color quantum numbers are r, b, g (for 'red', 'blue', and 'green'). Only white baryons are observed in experiment. Thus the color wave function corresponds to a color singlet state and is therefore completely antisymmetric. As a consequence the rest of the wave function (comprising spatial, spin, and flavor degrees of freedom) must be symmetric.

2.2. Flavor

According to the Standard Model (SM) of particle physics there are six quark flavors: up, down, strange, charm, bottom, and top. Quarks of different flavours have different masses. Normal hadronic matter (i.e. atomic nuclei) is basically composed only of the so-called light flavors u and d. CQMs consider hadrons with flavors u, d, and s. These are also the ones that are most affected by the SBχS. Correspondingly, one works in $SU(3)_F$ and deals with baryons classified within singlet, octet, and decuplet multiplets. For example, the nucleons (proton and neutron) are in an octet, together with the Ξ, Σ, and Λ particles.

2.3. Spin

All quarks have spin $\frac{1}{2}$. The spin wave function of the three quarks is constructed within $SU(2)_S$ and is thus symmetric or mixed symmetric or mixed antisymmetric. The total spin of a baryon is denoted by S.

2.4. Orbital Angular Momentum and Parity

The spatial wave function corresponds to a given orbital angular momentum L of the three-quark system. Its symmetry property under spatial reflections determines the parity P.

2.5. Total Angular Momentum

The total angular momentum J is composed of the total orbital angular momentum L and the total spin S of the three-quark system according to the quantum-mechanical addition rules of angular momenta: $J = L + S$. It is always half-integer. The total angular momentum J is a conserved quantum number and, together with the parity P, serves for the distinction of baryon multiplets J^P.

3. QUANTUM SPECTRA OF BARYONS

The various CQMs produce baryon spectra with characteristic differences due to the underlying hyperfine interactions. In Fig. 1 the excitation spectra of the nucleon (N) and delta (Δ) particles are shown for three different classes of modern relativistic CQMs. While the ground states are practically the same (and agree with experiments) for all CQMs, the excited states show different level orderings. For instance, in the OGE CQM the first excitation above the N ground state is $J^P = \frac{1}{2}^-$, whereas for the GBE CQM it is $J^P = \frac{1}{2}^+$. Evidently the GBE CQM reaches the best overall agreement of its predictions with the available experimental data.

4. SONIFYING MASS SPECTRA

The baryon spectra as visualised by patterns such as in Fig. 1 allow a discrimination of the qualities of the CQM description of experiment. Also one can read off characteristic features of the different CQMs such as the distinct level orderings etc. However, it is certainly difficult to conjecture specific symmetries or other relevant properties in the dynamics of a given CQM by just looking at the spectra. Here, sonification may provide a more useful tool to bring about such detailed features inherent in the baryon spectra.

We have started our sonification studies of baryon spectra by attempts for an auditory discrimination between spectra of different particles, such as the N and the Δ. Can one distinguish between these families of particles by listening only?

Furthermore, we have also studied the sonification of multiplets with different parities P and different total angular momenta J. In addition, we have tried to find means for auditorily discerning between spectra from CQMs with different dynamics or with no hyperfine interaction at all. For example, can one hear the differences between the OGE and GBE CQMs, and how distinctly does a spectrum sound if only the confinement interaction is present?

We consider these studies as exploratory steps towards a more profound investigation of quantum spectra by means of sonification. It appears as an exciting possibility to bring about additional evidences in the properties of such data sets than is achieved by visualisation.

4.1. Data Details

So far we have studied the sonification of baryon spectra along three specific data sets. They contain the N as well as Δ ground state and excitation levels for three different dynamical situations: 1) the GBE CQM [7], 2) the OGE CQM [5], and 3) the case with the confinement interaction only (no hyperfine interaction being present in the Hamiltonian of eq. (1)). Each one of these data files is made up of 20 lists, and each list contains the energy levels of a particular N as well as Δ multiplet J^P. The lists are different in length. Depending on the given J^P multiplet they contain 2–22 entries, since we only take into account energy levels up to a certain limit. Of

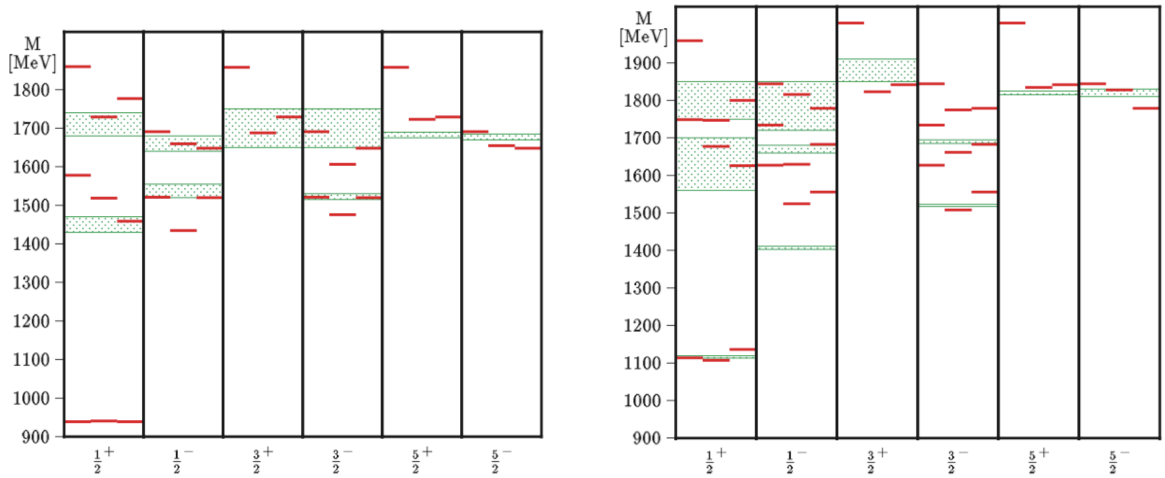

Figure 1. *N (left) and Δ (right) excitation spectra for three different types of relativistic CQMs (masses in MeV). In each column of a J^P multiplet, the left horizontal lines are the predictions of the OGE CQM [5], the middle ones of the II CQM [6], and the right ones of the GBE CQM [7]. The shaded boxes represent the experimental data with their uncertainties after the latest compilation of the Particle Data Group [11].*

course, at this stage the total number of entries is rather low. However, in the following the data sets can easily be extended by calculating more and more levels in the baryon spectra.

For sonification of the baryon spectra an immediate interesting feature is the level spacing. The quantum-mechanical spectrum is bounded from below and its absolute position is fixed by the *N* ground state (at 939 MeV). Therefore it is suggested to relate the differences between the energy levels to audible frequencies.

4.2. Exploratory Sonification Studies

In view of the static nature of the data as explained above, several simple strategies can immediately be followed for an auditory display of the spacings between the energy levels in the spectra, such as:

i) Mapping the mass spectra to frequency spectra directly, with tunable transposition together with optional linear frequency shift and spreading;

ii) Mapping the (linear) mass spectra to a scalable pitch range, i.e. using perceptually linear pitch space as representation.

In our current implementations both of these approaches can be listened to as static spectra and also as tunable arpeggios against a background drone of the same spectrum. Flexible comparison between different subsets of the data is a key requirement for static data. E.g., in order to achieve a discrimination by parity *P*, one can choose to play interleaved sequences alternating between positive and negative parity.

These models are implemented in easily changeable SuperCollider3 scripts; for a more flexible browsing, a simple GUI has been made (see Fig. 2). All the tuneable playback settings can be changed while playing and they can also be saved for easy reproducibility and an exchange of settings. Some tuning options have been included in order to account for known data properties. E.g., for recognition of diminishing reliability of the values calculated for higher excitations in the mass spectra, we introduced a tuneable slope factor in all models.

Since this project has been started only recently, we do not yet have formal evaluations by domain experts. However, first exploratory tests show that there are audible similarities between families across all particle species for the different CQMs (for instance, OGE vs. GBE). In the case of the confinement interaction only, the reduced complexities of the mass spectra are well recognizable already in the sonification designs made hitherto.

4.3. Next Steps

Beyond the experiences made so far with the sonification of the *N* and *Δ* spectra we plan to explore a number of further aspects that may ultimately be relevant in the scientific study of the physics background.

6.3.1. Comparison with Experimental Data

As is seen from Fig. 1, there are several experimental data available for the energy levels. However, they are affected by experimental uncertainties. Consequently, their auditory display needs some adaptations. We aim at a principal discrimination between (sharp) theoretical data as deduced from the CQMs and (spread) phenomenological data measured in experiment. It will be very interesting to qualify the theoretical predictions vis-à-vis the experimental data.

6.3.2. Investigation of CQM Features

One can study the influence of the hyperfine interaction in a very transparent way by starting out from the case with the confinement interaction only and gradually turning on the strength of the hyperfine interaction from 0 to 100%. In this way the (considerable) changes in the mass spectra can be investigated when the initial degeneracy of the states is resolved and the level splittings grow in magnitude.

6.3.3. Macroscopic Mass Modelling

Referring to the concept of mass in macroscopic physics, we may also play with relating the spectral data to mass-spring-damping models with changeable, i.e. tuneable nonlinear damping functions. While there is no directly plausible physical implication for such kind of a sonification model (among others, the quantum world of baryons is also relativistic), we may expect that a coupled system of such masses will resonate in ways that express the properties of a group of excitation spectra in a perceptually relevant fashion – simply because of our everyday acoustic knowledge of complex resonators and their perceptual integration. As a variant of this approach, we also plan to explore a system of coupled pendula.

6.3.4. Spatial Ordering

We have not yet explored more detailed spatial ordering by data dimensions. For instance, we expect navigation in a spatial order determined by symmetry properties between particle groups to be interesting. The simple option of spatial spreading of individual spectral line resonators already has turned out to be helpful in terms of clarity of presentation.

6.3.5. Time Aspects

There are plenty of interesting time phenomena in the quantum domain, which can be made use of in numerous ways in further explorations. For example, there is an enormous variation in the half-life of the different particles. This could be expressed quite directly in differentiated decay times for every spectral line. In addition, including the probabilities for transitions between excited states and ground states will open promising possibilities for demonstrating the dynamical ingredients in the quark interactions inside baryons.

5. CONCLUSION

First investigations have indicated that sonification is an interesting alternative and a promising complementary tool for analyzing quantum-mechanical data. So far we have concentrated on sonifying only the mass spectra of baryons with limited data sets. Obviously, the consideration of expanded data sets and above all the extension to further particle properties will allow for much richer representations, which may well lead to valuable evidences not yet achieved otherwise. Technically, there are a number of good candidates for sonification approaches to be explored further in the context of quantum spectra.

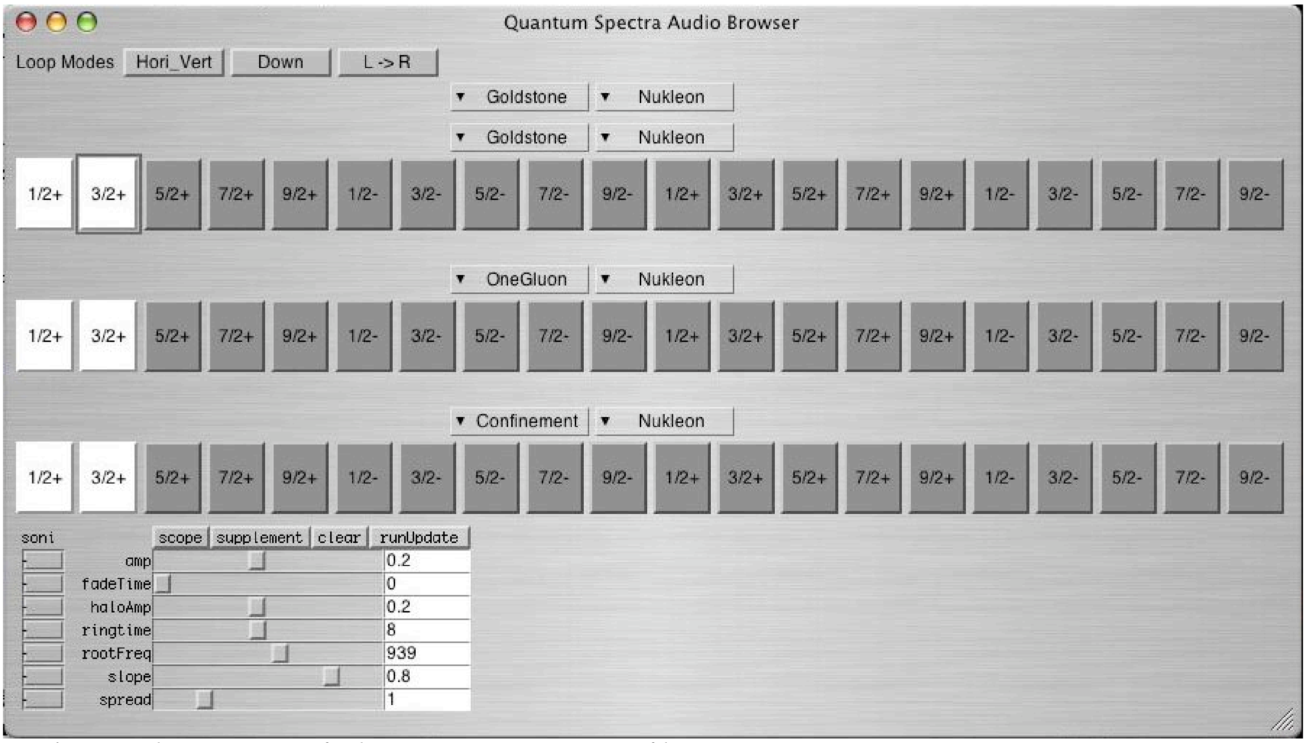

Figure 3. *The current GUI for browsing quantum spectra of baryons.*

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