SONIFICATION OF QUANTUM SPECTRA

ABSTRACT

This paper is about the sonification of the quantum spectra of subatomic particles called baryons. The data under investigation are generated by different competing models that describe particle properties and symmetries.

We report on the first experiments towards finding useful and valid strategies for displaying, exploring and comparing both model-generated and experimental data of particle properties and their interrelations by means of sonification.

1. INTRODUCTION

Baryons, most prominent among them the proton and the neutron, belong to the particle family of the hadrons. They are made up of quarks, the last known constituents of matter. The forces that determine their behavior are described within Quantum Chromodynamics (QCD). This theory is well established; e.g. the Nobel Prize 2004 was awarded for its development. Early on it was shown that QCD is solvable with arbitrary precision for high energies; however for middle and low energies, there are still no satisfying solutions. One must resort to effective theories or models. A promising approach is relativistic constituent quark models. One aims to set up models for baryons that allow for an effective description of their properties (like mass) and reactions based on QCD, and in accordance with all available experimental data for the low and middle energy regime.

These mass spectra data produced by different models are highly interrelated in complex ways, which makes them interesting candidates for exploration by means of sonification.

This project is part of an interdisciplinary research project [1] (started in January 2005), in which sonification specialists work with scientists from four domains to develop applications for their respective domains, and to eventually arrive at a generalized, flexible and easily extensible sonification environment.

2. CONSTITUENT QUARK MODELS

Constituent quark models have a long tradition, since the first model [2, 3] much has changed: a typical CQM is based on a Hamilton operator, which consists of a kinetic energy term and quark-quark interaction. The latter consists in turn of a confinement and a hyperfine interaction. Finding appropriate expressions for the interaction between quarks has been the focus of interest for decades. After all, the masses of baryons are largely determined by the form of the quark-quark interaction.

Quarks in nature are never observed on their own, they are only found confined within hadrons. In QCD this is known as confinement. The form of the confinement potential depends on the model used, but generally it gets stronger when one tries to separate two quarks.

The hyperfine interaction was first modeled by a gluon exchange potential [4], which eventually failed to reproduce the mass spectra of light and strange baryons: One cannot model all excitation levels at the same time to fit experimental data (see 3.2 for more on baryon flavors). Similar problems occurred when modeling the hyperfine interaction with a superposition of gluon and meson exchange [5], and later on with the instanton-induced interaction [6, 7].

Some years ago the Graz group [8] 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) at low energies. The resulting potential implies a dependency between spin and flavor, which fits well with the phenomenology. This model is well suited to reproduce the ordering of energy levels by parity, better than the models given above.

Generally, CQMs are relativistic, because quarks are confined within distances around 10-15 m and particle speeds can approach the speed of light. Under these circumstances, non-relativistic descriptions would make little sense.

The models we chose for sonification are the Goldstone-Boson Exchange model, the One-Gluon Exchange model, and for reference, a Confinement model which does not include a hyperfine interaction.

2.1. Goldstone-Boson Exchange Constituent Quark Model

This model is based on the Hamilton operator

$$H = H_0 + \sum_{i<j} \left[V_{conf}(i,j) + V_{hf}(i,j) \right] \tag{1}$$

where the first term is the kinetic energy, and the second the quark-quark interaction consisting of confinement and hyperfine interaction. The confinement is linear, i.e. it increases proportionally with the distance between two quarks. The hyperfine interaction is based on the exchange of Goldstone bosons. These are mesons, which occur because of the spontaneous breaking of symmetry in QCD at low energies. The established method for solving the eigenvalue problem of the Hamilton operator is the stochastic variational method [9].

While the original version of the Graz model is based on the exchange of pseudoscalar Goldstone bosons [8], there is an extended variant, where additionally to pseudo-scalar mesons also vector and scalar mesons are exchanged [10]. As the baryon spectra can effectively be reproduced quite well by the original model version, we are interested in experimenting with the simple version first.

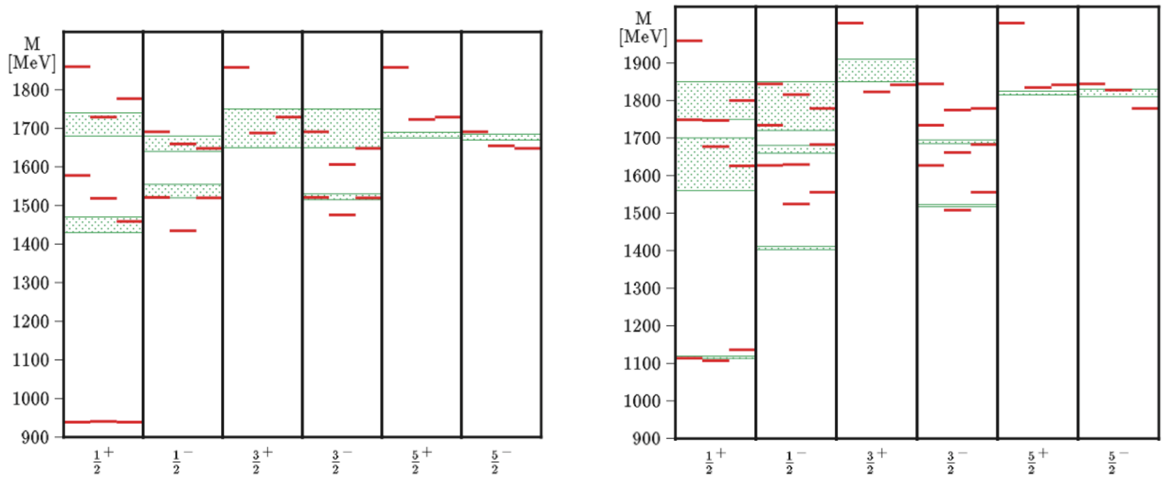

Figure 1. *Excitation spectra of Nucleon (left) and Delta (right) particles. In each column, the three entries left to right are the energies based on One-Gluon exchange [11], Instanton-induced [6,7], and Goldstone-Boson Exchange [8] constituent quark models. The shaded boxes represent experimental data and their imprecision ranges [12].*

2.2. One-Gluon Exchange Constituent Quark Model

This model is also based on a Hamilton operator like Equation 1, but the hyperfine interaction here is realized by a One-Gluon exchange potential. With this kind of interaction one can (as with a Goldstone-Boson model) reproduce features like the mass splitting between nucleon and delta particles which is observed in nature; but it is not possible to reproduce the 'Level-Ordering', i.e. the correct order of masses in the excitations spectra of nucleon and lambda particles. This results from the missing of the explicit flavor dependence in the hyperfine interaction of this model.

3. QUANTUM SPECTRA OF BARYONS

Calculating baryon spectra is a typical few body problem, which is solved in terms of relativistic quantum mechanics. After defining the hyperfine interaction and thus the dynamics of each model, here is a short explanation on the quantum numbers of baryons. These quantum numbers classify a baryon state and determine its baryon wave function. Then, the eigenvalue problem can be solved, e.g. with the stochastic variational approach [9].

3.1. Baryon Wave Functions

Within the framework of constituent quark models, baryons are seen as bound states of three constituent quarks. These quarks have various properties which are specified by respective quantum numbers: Spin S, which defines the intrinsic angular momentum, the angular momentum L, flavor F and color C. Quarks come in six flavors and three colors. Flavor and color have been introduced for reasons of symmetry, and like the spin, they serve to classify particles occurring in nature.

The resulting wave function ΨXSFC of a baryon is therefore a product of the spatial (X), spin (S), flavor (F) and color (C) degrees of freedom. Because only 'white' baryons are observed in nature, baryons are considered color singlets, which means the color aspect of the wave function is identical for all baryons; thus color can be disregarded for the models described here.

3.2. Baryon Classification

When visualizing the masses and thus the excitation spectra of baryons, we use a classification scheme as in Fig. 2. A baryon is characterized by a specific name, which derives from the flavor F, a total momentum J, and the parity P. A baryon state is thus called e.g. N1/2+, meaning a nucleon with a total momentum of 1/2 and positive parity.

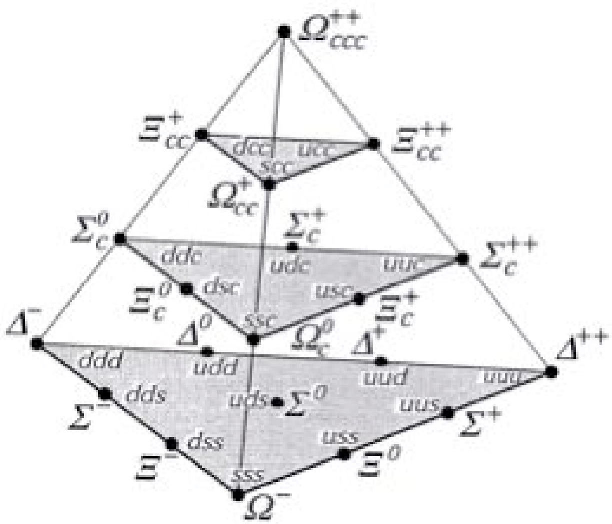

Figure 2. *Multiplet structure of the decuplet baryons as one example of baryon flavor symmetries. The lowest layer represents the sector of light and strange baryons.*

3.2.1 Flavor

There are six flavors of quarks: up, down, strange, charm, bottom and top. Up and down are very light, strange is a little heavier, and the others are very heavy. In Constituent Quark Models, mainly the baryons consisting of light and strange baryons have been investigated. The combination of three quarks with their flavors determines the name of each baryon type. For the strange and light baryons there are the nucleon N, delta Δ, lambda Λ, sigma Σ, xi Ξ and omega Ω. Figure 2 shows one schematic ordering by symmetry.

3.2.2 Angular Momentum and Spin

Quarks are Spin-1/2 particles. Together with the orbital angular momentum, one can find a total angular momentum J for each baryon, which in a quantum mechanical model derives from a coupling of spin and angular momentum.

3.2.3 Parity

The parity of a baryon derives from its orbital angular momentum. This quantum number describes its behaviour under spatial mirroring (mirror symmetry). If a parity transformation does not change the sign, then it is defined as positive parity, otherwise one speaks of negative parity.

4. SONIFYING MASS SPECTRA

While the basic properties of the models can be read and interpreted from baryon spectra, there are a number of open research questions where we expect sonification to be helpful. As we have a longer time frame for the whole project, we have started by identifying phenomena that are likely to be discernible in basic sonification experiments:

Is it possible to distinguish e.g. the spectrum of an N1/2+ nucleon from, say, a delta D3/2+ by listening only?

Is there a common family sound character for groups of particles, or for entire models?

In the confinement model, the intentionally absent hyperfine interaction causes data points to merge into one: is this clearly audible?

4.1. Data Details

Three specially made data files have been used for this project so far. All of them contain mass spectra for nucleon and delta in one model each: file 1 is from the Goldstone-Boson exchange CQM [8], file 2 is from One-Gluon exchange [10], and file 3 for a Confinement model. Each data file is made up of 20 lists, and each list refers to nucleon (or delta) for one value of JP. The data sets are different lengths (22 – 2 entries), because we chose a mass limit for each data file. For the Goldstone-Boson model we have set this limit to 3842.597 MeV; this is the 15th value for N1/2-.

While the total number of data points is rather low, the interrelations and symmetries are quite complex. In the current experiments, most of these symmetries are not portrayed yet.

The most interesting dimension to start with is that of the mass differences, the level ordering. Because the energy level of the nucleon in its fundamental state is known to be quite precisely 939 MeV in nature, one can shift all masses for each model accordingly; then the absolute values of the data (and thus the proportions between values) can also be considered relevant.

4.2. Initial Sonification Approaches

Given the static nature of the data, and that the spacings between spectral lines are the main focus, a number of very simple strategies suggest themselves to be tried first:

Mapping mass spectra to frequency spectra directly, with tunable transposition, and optional linear frequency shift and spreading.

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

In our current implementations both of these can be listened to as static spectra, as well 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 do comparisons by parity, one can choose to play interleaved sequences alternating between parity + and -.

These models are implemented in easily changeable SuperCollider3 scripts; for more flexible browsing, a simple GUI has been made (Figure 3). All the tunable playback settings can be changed while playing, and saved for easy reproducibility and exchange of settings.

Some tuning options have been included to account for known data properties; e.g. to account for the diminishing reliability of the values calculated for higher excitation orders, we introduced a tunable slope factor in all models.

Because this project has only started very recently, we do not have formal evaluations by domain experts yet; however, first informal tests show that there are audible family similarities across all particles in one model, and that the reduced complexity of the confinement model is well recognizable already in our first sonification designs.

4.3. Next Steps

So far we have concentrated on sonifying mass spectra only; obviously introducing more particle properties will allow for richer representations that we expect to be of heuristic value. Apart from that, there is a number of strategies that we plan to explore:

4.3.1 Comparison with Experimental Data

As figure 1 shows, there are experimental data for the particle properties we deal with in these models. Because these have a known range of measurement imprecision, they cannot be directly compared to the model data, but minor adaptations of the current synthesis models should allow us to express these data and their imprecisions. We expect that comparing for family similarities between experimental and model data will be very interesting.

4.3.2 Adjusting Constituent Quark Model Parameters

We have produced data where the hyperfine interaction part of the quark-quark interaction is continuously 'turned up' from 0 to 100%. This data set may turn out to be interesting for understanding how the collapse of data points into single points proceeds, and for learning to follow and identify spectral changes like this by listening.

4.3.2 Macro-Physical Mass models

Taking the notion of mass more literally and transferring it to the macro domain, we intend to put masses with the values from our data into mass-spring-damping models with changeable, i.e. tunable nonlinear damping functions. While there is no directly plausible physical analogy for this kind of sonification model (among other things, the quantum world in which baryons exist is relativistic), we expect that a coupled system of such masses will resonate in ways that express the family 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 pendulums (both in serial and parallel configurations).

4.3.3 Spatial Ordering

For reasons of simplicity, we have not explored more detailed spatial ordering by data dimensions yet, and we expect e.g. navigation in a spatial order determined by symmetry relations 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.

4.3.4 Time Aspects

There are plenty of interesting time phenomena in the quantum domain which can be applied in numerous ways in further experimentation; e.g. there is enormous variation in the half life of the different particles, which could be expressed quite directly in differentiated decay times for every spectral line.

Finally, employing the probabilities for transitions between excitation states for more dynamic models of the quantum world that include particle behavior and not just static properties would be quite intriguing to us.

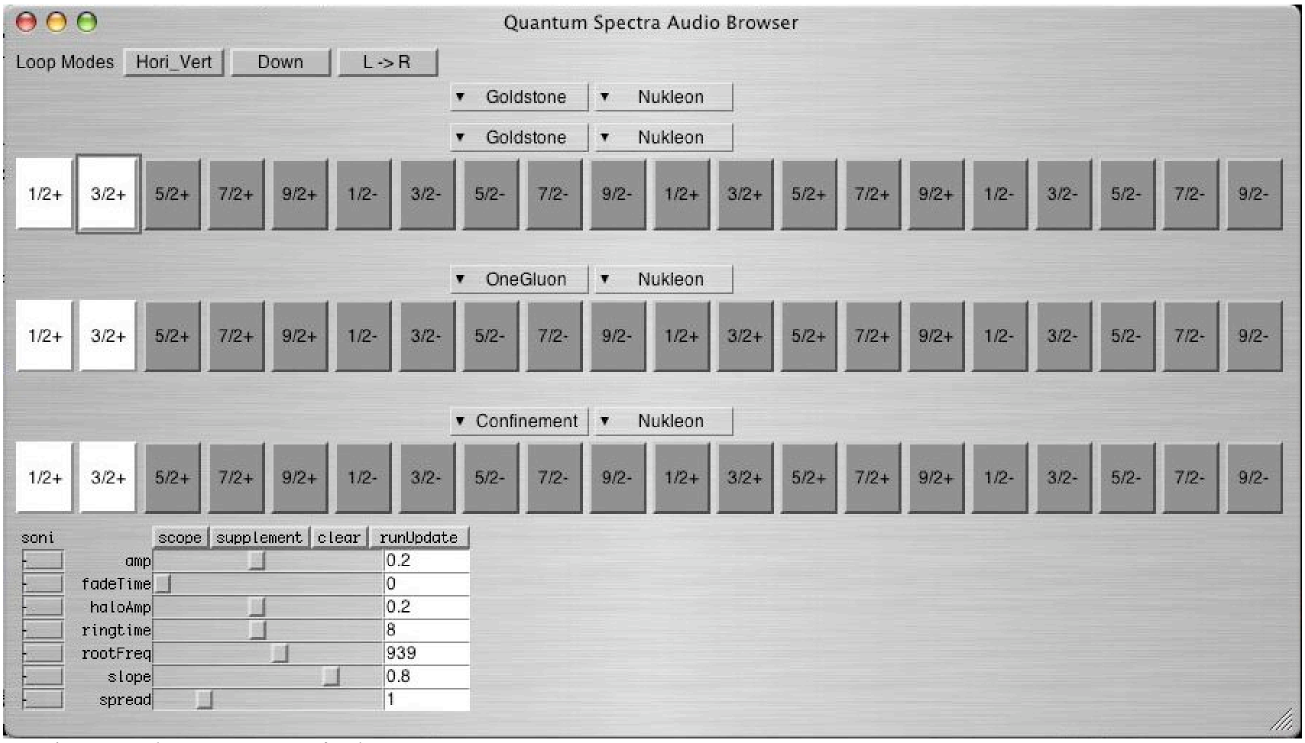

Figure 3. *The current GUI for browsing quantum spectra.*

5. CONCLUSION

First experiments indicate that sonification is an interesting alternative and complement for analyzing quantum spectra data. There are many more good candidates for approaches to be explored, and we are looking forward to continue working along the lines described.

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