INTRODUCTION

Perhaps the greatest challenge facing those of us working in the area of strong interaction physics is to be able to rigorously compute the properties and interactions of nuclei. The many decades of theoretical and experimental investigations in nuclear physics have, in many instances, provided a very precise phenomenology of the strong interactions in the non-perturbative regime. However, at this point in time we have little understanding of much of this phenomenology in terms of the underlying theory of the strong interactions, Quantum Chromo Dynamics (QCD). I wish to discuss a strategy for making a connection between QCD and nuclear physics, which ultimately will allow for the calculation of nuclear properties and processes in terms of the light quark masses, the scale of the strong interactions, and the electroweak couplings.

QCD TO NUCLEI: STRATEGY

The ultimate goal is to be able to rigorously compute the properties and interactions of nuclei from QCD. This includes determining how the structure of nuclei depend upon the fundamental constants of nature. Perhaps as important, we would then be in the position to reliably compute quantities that cannot be accessed, either directly or indirectly, by experiment.

The only way to rigorously compute strong-interaction quantities in the nonperturbative regime is with lattice QCD. One starts with the QCD Lagrange density and performs a Monte-Carlo evaluation of Euclidean space Green functions directly from the path integral. To perform such an evaluation, space-time is latticized and computations are performed in a finite volume, at finite lattice spacing, and at this point in time, with quark masses that are larger than the physical quark masses. To compute any given quantity, contractions are performed in which the valence quarks that propagate on any given gauge-field configuration are “tied together”. For simple processes such as nucleon-nucleon scattering, such contractions do not require significant computer time.
compared with lattice or propagator generation. However, as one explores processes involving more hadrons, the number of contractions grows rapidly (for a nucleus with atomic number $A$ and charge $Z$, the number of contractions is $(A + Z)!/(2A - Z)!$), and a direct lattice QCD calculation of the properties of a large nucleus is quite impractical simply due to the computational time required.

The way to proceed is to establish a small number of effective theories, each of which have well-defined expansion parameters and can be shown to be the most general form consistent with the symmetries of QCD. Each theory must provide a complete description of nuclei over some range of atomic number. Calculations in two “adjacent” theories are performed for a range of atomic numbers for which both theories converge. One then matches coefficients in one EFT to the calculations in the other EFT or to the lattice, and thereby one can make an indirect, but rigorous connection between QCD and nuclei. It appears that four different matchings are required:

1. **Lattice QCD.** Lattice QCD calculations of the properties of the very lightest nuclei will be possible at some point in the not so distant future [1]. Calculations for $A \leq 4$ as a function of the light-quark masses, would uniquely define the interactions between nucleons up to and including the four-body operators. Depending on the desired precision, one could possibly imagine calculations up to $A \sim 8$.

2. **Exact Many-Body Methods.** During the past decade one has seen remarkable progress in the calculation of nuclear properties using Green Function Monte-Carlo (GFMC) with the $AV_{18}$-potential (e.g. Ref. [2]) and also the No-Core Shell Model (NCSM) (e.g. Ref. [3]) using chiral potentials. Starting with the chiral potentials, which are the most general interactions between nucleons consistent with QCD, one would calculate the properties of nuclei as a function of all the parameters in the chiral potentials with GFMC or the NCSM out to some given order in the chiral expansion. A comparison between such calculations and lattice QCD calculations will determine these parameters to some level of precision. These parameters can then be used in the calculation of nuclear properties up to atomic numbers $A \sim 20 – 30$. The computer time for these many-body theories suffers from the same $\sim (A!)^2$ blow-up that lattice QCD does, and for a sufficiently large nucleus, such calculations become impractical.

Another recent development that shows exceptional promise is the latticization of the chiral effective field theories [4, 5, 6, 7, 8]. This should provide a model-independent calculation of nuclear processes once matched to lattice QCD calculations.

3. **Coupled Cluster Calculations.** In order to move to larger nuclei, $A \lesssim 100$ a technique that has shown promise is to implement a coupled-clusters expansion (e.g. Ref. [9]). One uses the same chiral potential that will have been matched to lattice QCD calculations, and then performs a diagonalization of the nuclear Hamiltonian, after truncating the cluster expansion, which itself contains arbitrary coefficients. The results of these calculations will be matched to those of the NCSM or GFMC for $A \sim 20 – 30$ to determine the arbitrary coefficients. This method is unlikely to be practical for very large atomic numbers.

4. **Density Functional Theory (?) and Very Large Nuclei** To complete the periodic table one needs to have an effective theory that is valid for very large nuclei and
nuclear matter. A candidate that has received recent attention is Density Function Theory (DFT) (e.g. Refs. [10, 11]). It remains to be seen if this is in fact a viable candidate. There is reason to hope that this will be useful because there is clearly a density expansion in large nuclei with a power-counting that is consistent with the Naive Dimensional Analysis (NDA) of Georgi and Manohar [12]. The application of DFT to large nuclei is presently the least rigorously developed component of this program.

The latticized chiral theory mentioned previously can also be applied to the infinite nuclear matter problem. This work is still in the very earliest stages of exploration, but this looks promising [6].

**QCD TO NUCLEI: ONE OF THE CHALLENGES**

An intriguing aspect of nuclear physics and QCD that has slowed the theoretical progress in connecting QCD to nuclear physics is the fine-tunings that are present. I will discuss just two of these fine-tunings.

\[ 3\alpha \rightarrow ^{12}C \]

Perhaps the most famous fine-tuning is that observed in the triple-$\alpha$ process. The production of carbon in stars results from the reactions $3\alpha \leftrightarrow \alpha + ^8Be \leftrightarrow ^{12}C^{*\ast}$ being in thermal equilibrium. Because the ground state of $^8Be$ is barely unbound and the second excited state in $^{12}C$ is where it is, these reactions can simultaneously be in thermal equilibrium at temperatures $\sim T_8$. Further, the state in $^{16}O$ that could potentially be populated via $\alpha + ^{12}C$ is sub-threshold, and there is a large energy splitting to the next state in $^{16}O$, preventing significant carbon destruction. Much has been made about the positions of these levels, and in fact the location of the $^{12}C^{*\ast}$ was predicted prior to its discovery based upon anthropic arguments. Of the many possible universes with random values of the fundamental constants, as might arise from the landscape [13, 14] scenario in string theory, sufficient $^{12}C$ will be produced to support carbon-based life only in those universes with energy levels in the $A = 12$ system that are very close to those observed.

As a first step toward understanding these fine-tunings, there has been recent work in which limits have been placed on the variation in the magnitude of the nucleon-nucleon (NN) potential that is consistent with the production of significant amounts of $^{12}C$. It was found that a change of $\sim 0.5\%$ in the strength of the NN interaction was sufficient to yield a universe that does not contain significant amounts of $^{12}C$ or $^{16}O$ [15, 16]. There has also been recent work exploring the dependence of $^{12}C$ and $^{16}O$ abundances upon the location of the $^{12}C^{*\ast}$ level [17].

What is at the heart of these fine-tunings is not so much the absolute location of the energy-levels, but their relative location. It is unlikely that the simplest variations that one can imagine, changing the energy of only the $^{12}C^{*\ast}$ level and determining abundances, actually provide an indication of how robust this system is. It would be a wonderful accomplishment to explore every aspect of these systems, and these fine-tunings in terms of the fundamental parameters of nature, the light-quark masses $m_q$. 
the scale of the strong interaction $\Lambda_{\text{QCD}}$, and the electromagnetic coupling $\alpha_e$. However, at present we are far from being able to perform such a study due to both a lack of computational power, and a lack of theoretical infrastructure. Only crude estimates of how nuclear properties and interactions depend upon the fundamental constants are possible [18, 19].

When considered in terms of QCD, as opposed to nuclear structure, the fine-tunings in this system are quite severe. The location of the $i^{th}$ energy level is of the form

$$E_i = \Lambda_{\text{QCD}} f_i\left(\frac{m_u}{\Lambda_{\text{QCD}}}, \frac{m_d}{\Lambda_{\text{QCD}}}, \frac{m_s}{\Lambda_{\text{QCD}}}, \alpha_e\right),$$

(1)

and given that the scale of strong interactions is hundreds of MeV, and the allowed variation in the relative location of the level in $^{12}$C is $\sim 100$ keV, there is a fine-tuning between the $f_i$ at the level of $10^{-4}$.

**Nucleon-Nucleon Interactions**

The NN interaction itself is finely-tuned. The NN potential can be roughly separated into three distance-scales, the long-range part, the intermediate range part and the short-distance part. The long-range part is unambiguously described by one-pion-exchange (OPE), both theoretically and also by fitting to the multitude of scattering data. The intermediate range interaction (attraction), which traditionally was considered to result from the exchange of a “$\sigma$-meson”, has recently been shown to be the result of two-pion exchange (TPE) [20] as calculated using chiral perturbation theory ($\chi$PT). There is no reason to believe that the short-range component of the potential is describable in terms of meson exchanges, and the “best” potentials (defined by the value of $\chi^2$ in fitting) have some short-distance functional form consistent with power-counting expectations from effective field theory (EFT). The typical distance scale of the long-distance component is $\sim 1/m_\pi$, of the intermediate range component is $\sim 1/(2m_\pi)$, and of the short-distance component is $\sim 1/m_\rho$. The S-wave NN wavefunctions emerging from these potentials are essentially horizontal, which is highly unnatural and requires a fine-tuning between the various component of the potential. The deuteron has a binding energy of $\sim 2.2$ MeV, and the scattering length in the $^1S_0$-channel is $\sim -24$ fm. The EFT describing the NN interaction [21, 22, 23, 24, 25, 26] is considerably different to EFT’s that one is familiar with. For most EFT’s one can count the dimension of an operator and determine the size of its contribution to a process. This is not true for the EFT describing NN interactions, as one has to perform an expansion about a non-trivial, unstable infrared fixed point in the renormalization group (RG) flow [24, 25, 27, 28]. The implication of this is that the dimension-6 four-nucleon operator contribution to NN-scattering is not suppressed compared to that from the dimension-4 pion-nucleon interaction. In fact, in the $^1S_0$ channel, the long-distance pionic effects can be treated as a perturbation [24, 25, 29] and the full utility of the RG is explicit.
QCD TO NUCLEI: STATUS

During the past few years there has been substantial progress toward being able to compute nuclear properties from QCD using the strategy already outlined.

Lattice QCD

Lattice QCD has entered an era in which reliable calculations of strong interaction quantities can be performed with fully-dynamical QCD calculations at small lattice spacings and in large volumes (large and small are defined relative to the scale of chiral symmetry breaking). The lattice actions have good chiral symmetry through the invention of Domain-Wall fermions \[30, 31\] and Overlap fermions \[32\]. Further, there has been substantial progress in chiral EFT’s that, in addition to describing the light-quark mass dependence and allowing for rigorous chiral extrapolations, facilitate the removal of finite-lattice spacing \[33\] and finite-volume effects inherent in the lattice QCD calculations, e.g. Refs. \[34, 35\].

There has been much effort over the years to precisely determine strong interaction matrix elements required to extract parameters of the electroweak theory, such as \(V_{bc}\). A subset of these were described in Chris Sachrajda’s talk \[36\], and I will not discuss them here. A recent calculation involving the light mesons of interest to nuclear physicists is the calculation of \(I = 2 \pi \pi\) scattering in fully dynamical QCD by the NPLQCD collaboration \[37\], as shown in fig. 1. One finds good agreement with the predictions of chiral perturbation theory, and the calculations are at small enough pion masses where the perturbative expansion is reliable (see also Ref. \[38\]).

![Figure 1](image-url)  
**FIGURE 1.** \(I = 2 \pi \pi\) scattering from fully-dynamical lattice QCD \[37\]. (This figure is taken from Ref. \[37\].)

Compared to the meson sector, there has been somewhat less emphasis on the baryon sector. However, this is changing through the significant investment in lattice QCD at the Jefferson Laboratory by nuclear physics DOE and SciDAC. There are several hundred processors available for lattice calculations, and more importantly is the work
of Robert Edwards and his team to develop and make available the lattice software suite Chroma [39, 40].

There has been very impressive recent work by LHPC [41] computing the matrix element of the light-quark axial current in the nucleon at low quark masses and large volumes, as shown in fig. 2. Further, there are some preliminary results from the NPLQCD collaboration for the nucleon-nucleon scattering lengths in fully-dynamical lattice QCD, as shown in fig. 3.

**FIGURE 2.** The light-quark isovector axial current matrix element in the nucleon computed in fully dynamical lattice QCD [41], and its chiral extrapolation. (This figure is taken from Ref. [41].)

**FIGURE 3.** The nucleon-nucleon scattering lengths in the $^1S_0$ channel (left panel) and the $^3S_1 - ^3D_1$ coupled channels (right panel) as a function of the pion mass. The light (green) and dark (black) sets of points denote present theoretical estimates of the quark-mass dependence of the scattering lengths based upon EFT arguments [42]. The QCD data points at $m_\pi \sim 500$ MeV and $\sim 600$ MeV are the preliminary results of the NPLQCD exploratory investigation, while the other data points are the results of a quenched calculation [43].

**Light Nuclei, Chiral Symmetry and the Renormalization Group**

There has been impressive progress in the calculation of properties of nuclei when the NN, 3N and 4N interactions are specified. Calculations using GFMC have developed to
the stage where, in addition to the ground states, the excited states of the light nuclei can be extracted [2]. The agreement between the calculated energy-levels and those observed is truly impressive, and clearly demonstrates the strength of this technique. An example of this agreement can be seen in fig. 4. One would like to see these calculations performed with chiral potentials, so that they could be matched to lattice QCD calculations of the future.

![Argonne v₁₈ With Illinois-2](image)

**FIGURE 4.** The spectra of the \( A = 6, 7, 8 \) nuclei computed with a GFMC from the \( AV_{18} \) and IL2 interactions [2]. (This figure is taken from Ref. [2].)

Classifying and computing the interactions between nucleons based upon the approximate chiral symmetry of QCD [21, 22, 23, 24, 25, 26] is now at an advanced stage of development, e.g. Refs. [44, 45, 46, 47]. Initiated by the pioneering papers of Weinberg

![Interactions](image)

**FIGURE 5.** Interactions between nucleons as classified in Weinberg’s power-counting scheme [21, 22]. The solid lines denote nucleons, while the dashed lines denote pions. (This figure is taken from Ref. [44].)
in the early 1990's, the field is currently at the stage of having determined the small expansion parameter and to have essentially determined (in terms of *apriori* unknown counterterms) the interactions between two, three and four nucleons out to four orders in the expansion [48], see fig. 5. The importance of this effort cannot be overstated. In order to make rigorous, model-independent predictions and calculations in nuclear physics, the most general form of the interactions consistent with QCD must be known. The established power-counting finds that contributions from operators involving four or more nucleons are parametrically suppressed. In addition to establishing a rigorous framework, the light-quark mass dependence of nuclear interactions is provided by these same interactions.

The RG is a valuable tool for studying quantum systems and has been employed by particle physicists for decades. In the course of developing the EFT’s for nuclear physics, it was shown that the RG is also a powerful tool for nuclear physics [24, 25, 26, 27, 28]. Important nuclear physics phenomenology has arisen from applying the RG framework to the modern phenomenological NN interactions, such as the $A_{1S}$ potential, CD-Bonn potential and Idaho A potential. It was shown that by evolving these potential down to a sufficient low scale, $\Lambda \sim 600$ MeV, they all coincide in momentum-space [50, 51] to what is now referred to as $V_{\text{low} k}$, (for a nice overview see Ref. [52]), as shown for the $1S_0$ channel in fig. 6. The success of the chiral EFT program for these interactions meant that this result had to be true. As the renormalization scale of $V_{\text{low} k}$ is lower than the typical scale of the hard-core interaction in the “bare”-potentials, the interactions are softer, and as a result the many-body calculations in nuclei are significantly more convergent than with the bare potentials.

**The No-Core Shell Model**

A significant step toward the rigorous calculation of nuclear properties is the development of the NCSM. The entire goal of this program is to implement effective interaction theory, and “take the model out of the shell model”. Historically, the shell model implies that there is a small number of “active” nucleons in shell model orbits outside an inert
core of nucleons. The Hamiltonian of the active space is diagonalized to yield the energy eigenstates and energies. The NCSM treats all nucleons as active particles. Some arbitrary but complete basis is chosen, conventionally that of a harmonic oscillator (HO), and the Hamiltonian is constructed in this basis for realistic NN, 3N and recently 4N interactions. If an infinite number of HO states were included in the calculation, the eigenstates and energies would be independent of the HO parameter. This is impractical, but as the model space in enlarged the eigenenergies and states become less dependent upon the scale of the HO. A sufficient number of HO levels can be included to obtain the desired precision (for a discussion see Ref. [53]). Recent calculations with the softer potentials that result from the chiral EFT’s or $V_{NLO}$ are very encouraging. In particular, calculations have been done for $A = 10$ with the NN interaction out to NNNLO, the 3-body interaction out to NNLO and fit to the properties of $A = 3$ and $A = 4$ nuclei. Fig. 7 shows the energy levels of $^{10}\text{B}$ computed in the NCSM with the CD-Bonn potential, and with the chiral potential \(^1\). Clearly, the convergence is greatly improved when the chiral potential is used.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure7.png}
\caption{The spectrum of $^{10}\text{B}$, determined in the NCSM with the CD-Bonn potential (left panel) and the chiral potential (right panel) outlined in the text, as a function of the size of the basis.}
\end{figure}

\section*{The Braaten-Hammer Conjecture}

An interesting conjecture was put forth a couple of years ago by Braaten and Hammer [54]. As discussed earlier, one has a rough idea of the quark mass dependence of the NN sector [42, 55, 56], see fig. 3. As the pion mass is increased, it is possible that the scattering lengths in both the $^1S_0$ and $^3S_1 - ^3D_1$ channels become large. In fact, considering the limits shown in fig. 3, when the pion mass is around $\sim 175$ MeV an additional shallow bound state appears in the spectrum of the triton, as shown in fig. 8. This prediction is something that could be explored with lattice QCD, once the formalism is put in place for dealing with 3-body systems in Euclidean space at finite-volume.

\footnote{I would like to thank Erich Ormand and his collaborators for allowing me to show these figures.}
Somewhat more tantalizing, and also something that could be explored with lattice QCD, is their conjecture that the up and down quark masses could be individually tuned to values for which the scattering lengths in both the $^1S_0$ and $^3S_1 - ^3D_1$ channels are infinite. In such a scenario, the system is invariant under discrete scale transformations toward the infrared [58], and the triton has an infinite number of bound states, with the energy of adjacent states related by $E_{n+1}^2 = 515 E_n^2$.

FIGURE 8. The binding momenta $\kappa = (m_B^3)^{1/2}$ of $pnn$ bound states as a function of the pion mass. The circles indicate the triton ground state and excited state. The crosses give the binding energy of the physical deuteron and triton, while the dashed lines give the thresholds for decay into a nucleon plus a deuteron (left curve) or a spin-singlet di-nucleon (right curve). (This figure is taken from Ref. [54].)

**SUMMARY AND OUTLOOK**

Important progress has been made in the areas necessary for calculation of the properties and interactions of nuclei from QCD. It appears that we are entering an era in which lattice QCD calculations in the $A = 2, 3, 4$ systems will be matched onto the few-nucleon chiral interactions. These interactions will then be used to compute the properties of nuclei via GFMC, the NCSM, or potentially the latticized chiral theory.

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