The underlying philosophy and motivation for quantum hadrodynamics (QHD), namely, relativistic field theories of nuclear phenomena featuring manifest covariance, have evolved over the last quarter century in response to successes, failures, and sharp criticisms. A recent revolution in QHD, based on modern effective field theory and density functional theory perspectives, explains the successes, provides antidotes to the failures, rebuts the criticisms, and focuses the arguments in favor of a covariant representation.
Outline of the Comment

Evolution

Revolution

Interlude: Brian’s voice from emails

Antidotes, Rebuttals, and Reinterpretations
Outline of the Comment

Evolution

Revolution

Interlude: Brian’s voice from emails

Antidotes, Rebuttals, and Reinterpretations
Evolution: Original Motivation

- **Walecka’s motivation (1974):**
  - To discuss neutron stars you need EOS to high density
  - Consistent theory for that needs explicit mesonic dof’s
  - Relativistic propagation of hadrons needed
  - Automatic causal restrictions on excitation modes
  
  “The only consistent approach . . . which meets these [objectives] is . . . a local, relativistic, many-body quantum field theory.”

- **Focus on nuclear many-body problem with renormalizable lagrangian densities to define models**
  - Extrapolate from empirical calibration data without new, unknown parameters
  - Faithful pursuit of framework:
    - Is renormalizable QHD feasible and practical?

- **Expand around large classical (mean) Lorentz scalar and vector fields, even at ordinary densities**
Evolution: Successes

- **MFT model applied to bulk and single-particle properties**
  - Reproducing empirical nuclear matter saturation $\Rightarrow$ scalar and vector mean fields $\approx$ several hundred MeV
  - Spin-orbit potential *predicted* for finite systems $\Rightarrow$ relativistic
  - MFT predicts the existence of the nuclear shell model
- Relativistic MFT models with nonlinear couplings as good as any competing energy density functional
- **Relativistic impulse approximation $\gg$ nonrelativistic IA**
  - Proton-nucleus scattering observables (spin dependence)
  - Fold MFT nuclear densities with free NN scattering matrix
- **Dirac Brueckner Hartree-Fock (DBHF) for correlations**
  - Small corrections to large MFT scalar and vector self-energies

Brian made key contributions to all of these developments, but pions and the quantum vacuum were always lurking . . .
Evolution: Difficulties

- Requirement that QHD models be renormalizable
  \[\implies\] two classes of problems

- Honest pursuit of QHD program required confronting them

- Problems from computing quantum loops (short-range physics) using long-range degrees of freedom

  - Loops ensure unitarity of scattering amplitudes
  - Baryon loops with valence nucleons
    \[\implies\] familiar many-body effects
  - Loops give modification of quantum vacuum in presence of valence nucleons
  - Meson loops \[\implies\] contribute to extended nucleon structure

- Problems from also trying to maintain chiral symmetry

  - Embed spontaneously broken \(SU(2)_L \times SU(2)_R\) chiral symmetry of QCD in renomalizable QHD
  - Linear sigma model (plus isoscalar vector) seems natural, with Walecka \(\phi = \text{chiral } \sigma\)
Evolution: Difficulties with loops

- Casimir effect (one loop) is finite ("RHA"), but agreement of nuclear predictions with experiment is degraded
  - Spin-orbit splittings in particular → undermines QHD motivation

- Nuclear matter energy density blown out of the water at two loops
  - Loop expansion not reliable

- Ring diagrams → "ghosts"
  - Vertex insertions impractical

Brian led the way in all of these: Exposed problems then actively searched for solutions.
**Evolution: Difficulties with chiral symmetry**

- **Sigma model at mean field**
  - Cubic and quartic scalar self-couplings *constrained*
  - Impossible to reproduce empirical saturation
- **Generic problems with σ**
  - Too heavy: fluctuations in charge densities
  - Too light: spectrum off
  - Linear realization fails!
- **Precursor to revolution**
  - Weinberg’s field transformation to pseudovector coupling
  - New (light) scalar, isoscalar field allowed \( \rightarrow \) Walecka \( \phi \)

Again, Brian set the agenda . . .

From rjf + bds papers
Outline of the Comment

Evolution

Revolution

Interlude: Brian’s voice from emails

Antidotes, Rebuttals, and Reinterpretations
Revolution: EFT/DFT Perspective

- Reinterpret QHD lagrangians as *non-renormalizable* effective field theory (EFT) lagrangians
  - Known long-range interactions constrained by symmetries
  - Generic short-range interactions
  - Division between characterized by breakdown scale \( \Lambda \)
  - EFT is a general parametrization of low-energy observables

- EFT perspective implies infinitely many low-energy QCD representations
  - But not all equally efficient or physically transparent
  - Lorentz covariant vs. nonrelativistic formulations is a *choice*

- For QHD, non-Goldstone-boson physics \( \implies \Lambda \approx 600\text{ MeV} \)
  - Only *essential* QHD dof’s are nucleons and pions
  - Pion interactions in nonlinear chiral representation
  - *Parametrize* NN interaction with exchange of *off-shell* mesons (or use point couplings)
Revolution: EFT/DFT Perspective

EFT/DFT picture proposed by Brian, Hua-Bin Tang, rjf, Dirk

- Sigma meson is a light scalar, isoscalar chiral-singlet field while pion is in non-linear representation
- MFT of Walecka-type QHD is consistent with chiral symmetry

Systematic calculations by exploiting separation of scales
- Apply Georgi/Manohar Naive Dimensional Analysis (NDA) and naturalness $\implies$ order-by-order truncation

Term in $L_{\text{QHD}}$ or energy functional $\implies c \left[ f_\pi^2 \Lambda^2 \right] \left[ \left( \frac{\bar{N}N}{f_\pi^2 \Lambda} \right)^\ell \frac{1}{m!} \left( \frac{\Phi}{\Lambda} \right)^m \frac{1}{n!} \left( \frac{W}{\Lambda} \right)^n \left( \frac{\nabla}{\Lambda} \right)^p \right]$

- Prescription for counting powers of $f_\pi \approx 94$ MeV and a mass scale $\Lambda \approx 600$ MeV $\implies$ dimensionless $c$ is $O(1)$ if natural
- Ratio $\Lambda/f_\pi \rightarrow g_s, g_v \approx 5-10$ is origin of strong QHD couplings
- Friar, Lynn, Madland first demonstrated naturalness in QHD

Need density functional theory (DFT) perspective as well
- Account for the successes of relativistic mean-field models without requiring a mean-field approximation
Revolution: EFT/DFT Perspective

- Covariant generalization of DFT energy functionals
  - Functionals of scalar density $\rho_s$ and baryon current $B_\mu$
  - Relativistic mean-field models $\Rightarrow$ Kohn-Sham (KS) systems
  - Local scalar and vector fields $\Rightarrow$ relativistic KS potentials

$$\left[-i \nabla \cdot \alpha + \beta (M - \Phi(r)) + W(r)\right] \psi_\alpha(x) = \epsilon_\alpha \psi_\alpha(x)$$

- Different representations: $\Phi$ and $W$ could be . . .
  - nonlinear functions of scalar mean fields $\phi, V_0$
  - sums of scalar and vector densities ($\rho_s, \rho_B$)
    $\Rightarrow$ point-coupling models

- KS DFT procedure is the same as mean-field prescription!
  - Mean-field functional approximates exact functional
  - *Includes* higher-order correlations (cf. quantum chemistry)
  - Truncation determined by NDA *power counting*

- Mean-field energy functional omits nonanalytic terms
  - Combined EFT and DFT $\Rightarrow$ systematically include them!
Outline of the Comment

Evolution

Revolution

Interlude: Brian’s voice from emails

Antidotes, Rebuttals, and Reinterpretations
**Self-consistency applied to other problems**

SEROT FOOTBALL RATINGS FOR NCAA DIVISION I TEAMS  
10-20-1997 02:05:01  
ALL GAMES WEIGHTED EQUALLY  
**** SEED RATINGS INCLUDED WITH WEIGHT .3  
THIS LIST TOOK 11 ITERATIONS  
ONLY GAMES AGAINST DIVISION I TEAMS ARE INCLUDED  
ADD 3 OR 4 POINTS TO THE HOME TEAM TO PREDICT A SPREAD

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“I assume the COMMENTS manuscript has been submitted. I’ve read it again a few times (compulsiveness is a terrible thing to waste) and I like it a lot.”

“Referee reports have also been piling up here. I think we should put a tax on manuscript submittal. It will make life easier for us and fix the deficit.”

“I resent the comment about incessant badgering. What I do is incessant Hoosiering. In any case, it’s better than incessant buckeyeing.”

“I’ve been meaning to call for the past three days, but Midterm Hysteria has swept over me like El Niño. The test is tomorrow, so hopefully we will return to the ground state soon. I’ll call when $T \approx 0.$” [all in good \TeX!]

“It’s no surprise to me that teaching a new course is taking up all of your time. I know how that goes. If you make any progress on negative sleep, let me know. There must be a branch cut somewhere, since I’m trying to analytically continue from positive sleep, but I can’t get there.”

“Obviously, one never knows if the physics is really ‘right’, since just because it works doesn’t mean it’s right. You just keep calculating more and more.”
Outline of the Comment

Evolution

Revolution

Interlude: Brian’s voice from emails

Antidotes, Rebuttals, and Reinterpretations
Antidotes, Rebuttals, and Reinterpretations

Nuclei are nonrelativistic systems because corrections to the kinetic energy are small.

- The important aspect of relativity for ordinary nuclei is not that nucleon momenta are comparable to rest mass!
- Corrections to the nonrel. kinetic energy are small at $\rho_{\text{equil}}$.

\[
\frac{\mathcal{E}}{\rho_B} = M + \left[ \frac{3k_F^2}{10M} - \frac{3k_F^4}{56M^3} + \frac{k_F^6}{48M^5} + \cdots \right] 
+ \frac{g_v^2}{2m_v^2} \rho_B - \frac{g_s^2}{2m_s^2} \rho_B + \frac{g_s^2}{m_s^2} \frac{\rho_B}{M} \left[ \frac{3k_F^2}{10M} - \frac{36k_F^4}{175M^3} + \cdots \right] 
+ \left( \frac{g_s^2 \rho_B}{m_s^2 M} \right)^2 \left[ \frac{3k_F^2}{10M} - \frac{351k_F^4}{700M^3} + \cdots \right] 
+ \left( \frac{g_s^2 \rho_B}{m_s^2 M} \right)^3 \left[ \frac{3k_F^2}{10M} - \cdots \right] + \cdots.
\]

- Maintaining covariance allows scalars to be distinguished from the time components of four-vectors.
- Velocity dependence in scalar interaction $\implies$ higher-than-linear-order corrections in $\rho_B$.
- Leading corrections are repulsive $\implies$ equilibrium point.
Antidotes, Rebuttals, and Reinterpretations

The success of nonrelativistic approaches shows that covariant approaches are wrong or unnecessary.

- Historically, these successes were used to cast doubt on relevance of large scalar and vector potentials.
- But in a nonrelativistic treatment of nuclei, the distinction between a potential that transforms like a scalar and one that transforms like the time component of a four-vector is lost.
- Leading-order contributions are opposite in sign $\Rightarrow$ underlying large scale of individual covariant potentials would be hidden in nonrelativistic central potential. (The scalar and vector terms add constructively in the nonrelativistic spin-orbit potential $\Rightarrow$ an uncharacteristically large result.)
- Furthermore, the EFT expansion implies that even potentials as large as 300 to 400 MeV are sufficiently smaller than the nucleon mass that a nonrelativistic expansion should converge, if not necessarily optimally.

Thus the success of nonrelativistic nuclear phenomenology provides little direct evidence about covariant potentials.
It is important to find specific observables that distinguish between relativistic and nonrelativistic theory.

- This pursuit will not be fruitful.
  - There are field transformations that connect relativistic (covariant) and nonrelativistic theories, with the ratios of the fields to the nucleon mass acting as the parameters controlling truncation.
  - These parameters are small enough that a nonrelativistic approach should reproduce relativistic results, although not necessarily at the same level of approximation.
  - The more appropriate question is: What is the most efficient representation?
It is more efficient to work with a nonrelativistic theory because large cancellations are built in.

- If an approximate symmetry enforced cancellation between scalar and vector contributions, then desirable to build cancellation into any EFT lagrangian or energy functional.
  - Chiral symmetry alone $\neq$ scalar-vector fine tuning.
  - If the cancellation is accidental or of unknown origin, hiding the underlying scales may be counterproductive.
  - We argue that nuclei naturally fall into the second category, with the relevant scales set not by the nonrelativistic binding energy and central potential (tens of MeV), but by the large covariant potentials (hundreds of MeV).
Antidotes, Rebuttals, and Reinterpretations

It is more efficient to work with a nonrelativistic theory because large cancellations are built in.

- The signals of large underlying scales are patterns in the data that are simply and efficiently explained by large covariant potentials, but which require more complicated explanations in a nonrelativistic treatment. Examples:
  - The spin-orbit force, which appears automatically with the observed strength in a covariant formulation.
  - Medium-energy proton–nucleus spin observables, reproduced by relativistic IA with intuitive real optical potentials.
  - Energy dependence of the optical potential for N–nucleus scattering up to 100 MeV: \( V_0(E) \approx 52 \text{ MeV} - 0.3E \)
    - Naturally arises from Dirac equation with large fields:
      \[
      V_{\text{opt}}(E) \equiv \frac{1}{2M} \left[ M^2 - M^*^2 + W^2 \right] - \frac{W}{M} E \]
  - Nonrelativistic treatment needs nonlocal exchange terms
  - Scalar, isoscalar part of the NN kernel below 1 GeV: chiral symmetry, unitarity, \( \pi\pi \) interaction imply integrated strength \( \implies \) large scalar potential
“It’s the spin-orbit, stupid!”

The fine structure in atomic systems (left, from Bjorken and Drell) cannot be seen if levels drawn to scale.

The “fine” structure in nuclei (right, from Mayer/Jensen) is really “gross” ⇒ important relativistic effects
Proton-nucleus scattering observables

- Relativistic Impulse Approximation with large potentials reproduces medium-energy proton-nucleus data most efficiently
  - Nonrelativistic requires full-folding, medium effects
- Radial shapes of (real) optical potentials
  - Dirac: look like nuclear density profiles
  - Schrödinger: qualitative energy dependence, not intuitive
Antidotes, Rebuttals, and Reinterpretations

There is no experimental evidence of large scalar and vector fields.

- No *direct* experimental verification (or refutation) of *any* nuclear potentials.
  - Evidence that a natural representation contains large fields, which is achieved only with a covariant formulation, comes from both empirical and theoretical analyses of NN scattering and nuclear properties.
  - Again: manifestation of QCD scales translates in many instances into simpler, more efficient, more compelling explanations of nuclear phenomena than in nonrelativistic formulations.

- Instead, we ask if large fields can naturally appear . . .
Antidotes, Rebuttals, and Reinterpretations

There is no experimental evidence of large scalar and vector fields.

- **Empirical** support from nuclear properties from study of covariant density functionals fit to nuclei.
  - A good fit to nuclear properties requires the local scalar and vector potentials to be roughly 300–400 MeV.
  - The hierarchy of energy contributions follow NDA predictions.

- **Top**: Spin-orbit splitting \( \Rightarrow M^*/M \approx 0.6 \rightarrow \Phi \approx 350\text{ MeV} \)

- **Bottom**: If \( \Phi \) is large, \( W \) is large!

\[ \begin{align*}
\Phi_0 (\text{MeV}) & \quad W_0 (\text{MeV}) \\
0 & \quad 0 \\
100 & \quad 100 \\
200 & \quad 200 \\
300 & \quad 300 \\
400 & \quad 400 \\
\end{align*} \]
We know that mean-field theory cannot be a correct description of nuclei because important long- and short-range correlations are omitted.

- Mean-field models are approximate implementations of Kohn–Sham density functional theory, which means that correlation effects are included in simple Hartree calculations.
- Moreover, the “Hartree dominance” of the single-particle potentials has been demonstrated, implying that short-range correlation corrections are no more than tens of MeV.
- The bulk properties of interest in mean-field phenomenology are primarily isoscalar observables that involve low resolution, so long-range pionic correlations are of minor importance; for other observables, EFT provides a systematic framework for explicitly including pionic contributions.
Antidotes, Rebuttals, and Reinterpretations

The relativistic mean-field approximation may be valid at high densities, but nuclei are low-density systems.

- Modern view: successes of relativistic mean-field theory do not depend on the justification of the mean-field approximation at high density, but on the flexibility of the mean-field density functional near equilibrium density. The combination of EFT and DFT concepts and methods applied to mean-field models of nuclei reveals that:
  - NDA provides an organizational principle for the EFT. Power counting and the limited number of bulk nuclear observables explain the success of conventional mean-field models, which contain fewer parameters than the most general EFT models.
  - Vacuum effects, chiral symmetry, and nucleon substructure are all included in general QHD models.
  - Ground-state nuclear properties provide information at low resolution. Models with different degrees of freedom (e.g., four- vs. two-component nucleons or point-coupling vs. meson models) are simply different organizations of the EFT. All are consistent with NDA.
Antidotes, Rebuttals, and Reinterpretations

QHD calculations apply perturbation theory, which is not sensible with large coupling constants.

- In fact, QHD does have a sensible expansion, which is not in powers of the couplings.
  - We work instead with density functional theory, with NDA power counting identifying reasonable expansion parameters.
- It is true that the short-distance (UV) behavior may be incorrect
  - but the EFT can correct the behavior systematically for low-energy observables
  - only a small number of parameters are needed

Organize expansion by:

\[ \nu = (\text{derivatives}) + \frac{(\text{nucleon fields})}{2} + (\text{# of non-Goldstone bosons}) \]
Antidotes, Rebuttals, and Reinterpretations

Relativistic many-body calculations have unquantifiable errors.

- The EFT framework based on NDA and naturalness provides an organizational scheme
  - for truncating a lagrangian or energy functional
  - for making well-defined error estimates
- Vacuum corrections, which disrupted early attempts at QHD expansion schemes, are
  - innocuous in the EFT approach
  - automatically absorbed into the coefficients
QHD does not have pions and chiral symmetry.

- Modern QHD effective lagrangians include pions in a nonlinear realization of chiral symmetry.
  - Confusion about the apparent absence of pions arises because *explicit* pionic contributions do not contribute to mean-field energy functionals, although correlated pionic contributions are *implicitly* contained in the effective scalar field.
  - Long-range pionic contributions can be included systematically, but do not qualitatively change mean-field phenomenology.
  - Calculations with explicit pions have been subsequently carried out (see below).
Local meson fields and “point” nucleons provide no possibility for quark substructure.

- This is simply incorrect.

- At energy and momentum scales small compared to the underlying QCD scale $\Lambda$, details of the quark substructure are not resolved.

- It follows that the substructure can be incorporated through a systematic expansion of nonlinear and gradient interactions in the effective lagrangian, with the dynamics encoded in the local hadronic couplings.

- This is the essence of the EFT approach.

- A clear example of this expansion is the single-nucleon structure included in modern QHD chiral lagrangians.
Antidotes, Rebuttals, and Reinterpretations

Virtual nucleon–antinucleon Z graphs, which are essential to relativistic phenomenology, should be suppressed because the nucleon has substructure.

- A local Dirac field for the nucleon does not imply a **physical** point nucleon.
- Moreover, the virtual \( \bar{N}N \) pair is **far off shell**, and the off-shell intermediate states in a particular representation cannot be interpreted in terms of on-shell physics.
- The EFT framework ensures that any incorrect short-distance dynamics can be corrected systematically with counterterms.
- Subsequent formulations of covariant chiral perturbation theory also verify that implicit Z graphs are not a problem, and that consistent power counting is possible.
Antidotes, Rebuttals, and Reinterpretations

The QHD treatment of the vacuum neglects nucleon substructure, violates $N_c$ counting rules, and relies on unphysical $\overline{NN}$ contributions (Z graphs).

- The modern QHD treatment of vacuum dynamics has changed this discussion completely.
  - Vacuum contributions in the EFT framework are not calculated explicitly but are implicitly and systematically contained in a small number of fitted parameters.
  - Any physical consequences of hadronic substructure, for example, are automatically included.
  - Furthermore, these implicit contributions are consistent with $N_c$ counting using NDA.
Antidotes, Rebuttals, and Reinterpretations

Hidden QCD color is relevant for low-energy nuclear physics and is not contained in QHD.

- **EFT perspective says this objection **must be irrelevant**
  - All observable amplitudes are color singles (color is confined)
  - EFT must be valid at sufficiently low energies, regardless of underlying QCD (without invoking colored dof’s)

Quantum chromodynamics of quarks and gluons is the fundamental theory of the strong interaction, so we should describe nuclei in terms of quarks.

- For most ordinary nuclear phenomena, a description based on hadronic degrees of freedom is most appropriate
  - Hadrons are the particles actually observed in experiments and thus are more efficient.
  - Hadronic calculations can be calibrated using empirical nuclear properties and scattering observables.
  - It is better to *match* the effective hadronic theory to QCD to determine its coefficients and then use the EFT to calculate nuclear structure and reactions.
The history of QHD from 1974 shows an evolution driven by the successes and difficulties of the original approach.

One of the cornerstones: the necessity for a consistent, microscopic treatment of nuclear systems using hadrons.

Modern viewpoint of QHD based on EFT and DFT

- Solves the most serious problems while preserving intact successful predictions for bulk and single-particle observables.
- EFT framework identifies the systematic “organizing principle” behind QHD: energy scales from underlying QCD define the dimensional analysis for terms in the effective lagrangian.
- Naturalness and the size of mean fields allow for practical expansion and truncation \(\Rightarrow\) scope and limitations of QHD.
- DFT and Kohn–Sham formalism explain why the truncated mean-field energy functional can be flexible enough to yield accurate results for (certain) nuclear observables.

A covariant formulation of the dynamics manifests the true energy scales of QCD in nuclei \(\Rightarrow\) efficient and comprehensive explanation of observed systematics.
Brian’s QHD Review Articles

  - With Dirk. Always referred to as “The Book”.
  - Over 2000 citations (ISI), include > 70/year for last 10 years!

  - Evolution: successes and difficulties.
  - Nearly 300 citations.

  - With Dirk. Documenting the revolution.
  - Nearly 500 citations.
Selected further developments

- **Subsequent papers by Brian and students**
  - “Two-loop corrections for nuclear matter in a covariant effective field theory,” Y. Hu, J. McIntire, B.D. Serot, NPA (2007) → loop expansion is ok!

- Electroweak interactions in a chiral effective lagrangian for nuclei: multiple papers by Xilin Zhang and Brian (2010–13)

- **A recent covariant effective field theory development:**
  - “Weinberg’s approach to nucleon-nucleon scattering revisited,” E. Epelbaum, J. Gegelia: “We propose a new, renormalizable approach to nucleon-nucleon scattering in chiral effective field theory based on the manifestly Lorentz invariant form of the effective Lagrangian without employing the heavy-baryon expansion.”