Combining gravity with the forces of the standard model on a cosmological scale

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Received 9 April 2010, in final form 9 May 2010
Published 17 June 2010
Online at stacks.iop.org/CQG/27/155008

Abstract
We prove the existence of a spectral resolution of the Wheeler–DeWitt equation when the underlying spacetime is a Friedman universe with flat spatial slices and where the matter fields comprise the strong interaction, with \( SU(3) \) replaced by a general \( SU(n) \), \( n \geq 2 \), and the electro-weak interaction. The wavefunctions are maps from \( \mathbb{R}^{4n+10} \) to a subspace of the antisymmetric Fock space, and one noteworthy result is that whenever the electro-weak interaction is involved, the image of an eigenfunction is in general not one dimensional; i.e. in general it makes no sense specifying a fermion and looking for an eigenfunction the range of which is contained in the one-dimensional vector space spanned by the fermion.

PACS number: 98.80.Qc

1. Introduction

In three former papers [9–11] we proved a spectral resolution of the Wheeler–DeWitt equation in the cosmological case—at least in principle. When the spatial slices of the underlying Friedman–Robertson–Walker universe are flat, we have developed a model in [11] with strictly positive energy levels—albeit for a single \( SO(3) \) gauge field. For a definition of positive energy levels in this situation, see [11, introduction].

In Friedman–Robertson–Walker models the matter Lagrangians must reflect the spacetime symmetries up to gauge transformations, and hence very special ansätze for the gauge fields have to be considered. For \( SO(n) \) resp. \( SU(n) \) gauge fields such ansätze are known for some time, cf [1, 13], but due to their special nature these ansätze introduce a number of non-dynamical variables into the Lagrangian resulting in additional first-class constraints. Hence, any attempt to generalize our previous results to higher dimensional gauge groups faced two major challenges: first, to handle these additional constraints and second, to handle a large number of dynamical bosonic variables—in fact any number larger than 1 posed a problem.
for the actual spectral resolution when an implicit eigenvalue problem for the gravitational Hamiltonian has to be solved and one has to prove that a (weighted) $L^2$-norm is compact compared with the gravitational energy norm. The former proof only worked in the case of a single bosonic matter variable.

These difficulties could be solved: the additional constraint equations are taken care of by considering a special infinite-dimensional subspace

$$E \subset C_\infty^c(\mathbb{R}^{4n+10}, \mathcal{F}),$$

where $\mathcal{F}$ is a finite-dimensional subspace of the antisymmetric Fock space, as the core domain, while in the case of the implicit eigenvalue problem the compactness property could be proved.

We consider as underlying spacetime a Friedman–Robertson–Walker space $N = N^4$ with flat spatial sections and the Lagrangian functional has the form

$$J = \alpha^{-1} M \int_\Omega (\bar{R} - 2 \Lambda) + \int_\Omega L_{M_1} + \int_\Omega L_{M_2},$$

where $L_{M_1}$ is the Lagrangian of the strong interaction, though we have replaced the $SU(3)$ connection by a general $SU(n)$, $n \geq 2$, connection, and $L_{M_2}$ is the Lagrangian for the electro-weak interaction.

The cosmological constant $\Lambda$ is very important, since it will play the role of an eigenvalue when we solve the implicit eigenvalue problem. It will turn out that $\Lambda$ has to be negative.

The core domain $E$ in (1.1) can be written as an orthogonal sum

$$E = \bigoplus_{1 \leq k, l \leq 9} E_{kl},$$

where

$$E_{kl} \subset C_\infty^c(\mathbb{R}^{4n+10}, F_{\sigma} \otimes F_{\rho}),$$

and $F_{\sigma}$ resp. $F_{\rho}$ are orthogonal subspaces in the fermion spaces $\mathcal{F}_1$ resp. $\mathcal{F}_2$ spanned by the fermions of the strong resp. electro-weak interaction. For the electro-weak interaction we have

$$\mathcal{F}_2 = \bigoplus_{1 \leq l \leq 9} F_{\rho l},$$

but the $F_{\sigma}$ fail to generate $\mathcal{F}_1$. Each of the $E_{kl}$ generates an infinite-dimensional Hilbert space $\mathcal{H}_{kl}$ in which we solve a spectral resolution for the Wheeler–DeWitt equation. Since the $\mathcal{H}_{kl}$ are mutually orthogonal, we can then define a spectral resolution in the orthogonal sum.

The main results can be summarized in the following.

**Theorem 1.1.** There exist 81 Hilbert spaces $\mathcal{H}_{kl}$ as described above, a detailed description will be given in the last three sections, and a self-adjoint operator $H$ in

$$\mathcal{H} = \bigoplus_{1 \leq k, l \leq 9} \mathcal{H}_{kl},$$

such that, for fixed $(k, l)$, there exists a complete sequence of eigenfunctions $\tilde{\Psi}_{ij} \in \mathcal{H}_{kl}$, $(i, j) \in \mathbb{N} \times \mathbb{N}$, with eigenvalues $\lambda_{ij}$ of finite multiplicities satisfying

$$H \tilde{\Psi}_{ij} = \lambda_{ij} \tilde{\Psi}_{ij},$$

$$0 < \lambda_{ij} \wedge \lim_{i \to \infty} \lambda_{ij} = \infty \wedge \lim_{j \to \infty} \lambda_{ij} = 0.$$
Let \( t \) be the variable which corresponds to the logarithm of the scale factor; then the rescaled eigenfunctions

\[
\Psi_{ij}(t, \cdot) = \tilde{\Psi}_{ij}(t - \frac{1}{2} \log \lambda_{ij}, \cdot)
\]

are the solutions of the Wheeler–DeWitt equation with the cosmological constant

\[
\Lambda_{ij} = -\lambda_{ij}^{-3}.
\]

Remark 1.2.

(i) Instead of considering both the strong and the electro-weak interactions each can be treated separately leading to similar results.

(ii) The method of proof can be applied to finitely many matter fields.

(iii) Whenever the electro-weak interaction is involved, the eigenfunctions \( \Psi \) in general cannot be written as simple products

\[
\Psi = u \eta,
\]

such that

\[
\eta \in \mathcal{F}_1 \otimes \mathcal{F}_2 \wedge u(x) \in \mathbb{C} \quad \forall x \in \mathbb{R}^{4 \times 10}.
\]

Thus, in general it makes no sense specifying a fermion \( \eta \) and looking for an eigenfunction \( \Psi \) satisfying

\[
R(\Psi) \subset \langle \eta \rangle.
\]

(iv) The number 81 of mutually orthogonal Hilbert spaces is due to the fact that the fermionic constraint operators \( \hat{I}_a \) resp. \( \hat{\lambda}_0 \) of the strong (SU(n)) resp. electro-weak interaction each have exactly nine eigenspaces due to their definitions as the sum of number operators.

2. Conventions and definitions

In this section we give a brief overview of our conventions and definitions.

We denote the Minkowski metric by \( \eta_{ab}, 0 \leq a, b \leq 3 \),

\[
(\eta_{ab}) = \text{diag}(-1, 1, 1, 1)
\]

and define the Dirac matrices accordingly

\[
\{\gamma^a, \gamma^b\}_+ = 2\eta^{ab}.
\]

\( \gamma^0 \) is anti-Hermitian and \( \gamma^4 \) Hermitian. When we are dealing with normal spinors, e.g. in the case of the strong interaction, we choose a basis such that

\[
\gamma^0 = i \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix}.
\]

However, when Weyl spinors are considered, e.g. in the case of the electro-weak interaction, we choose a basis such that the helicity operator \( \gamma^5 \) is represented as

\[
\gamma^5 = -\gamma^0 \gamma^1 \gamma^2 \gamma^3 = i \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix};
\]

then \( \gamma^0 \) has the form

\[
\gamma^0 = i \begin{pmatrix} 0 & I \\ I & 0 \end{pmatrix}.
\]
The $\gamma^k$, $1 \leq k \leq 3$, are defined by

$$\gamma^k = i \left( \begin{array}{cc} 0 & \sigma_k \\ -\sigma_k & 0 \end{array} \right)$$

(2.6)

in both cases, where $\sigma_k$ are the Pauli matrices.

Let $\psi = (\psi_a)$ be a spinor; then a bar simply denotes the complex conjugation

$$\bar{\psi} = (\bar{\psi}_a);$$

(2.7)

the symbol $\tilde{\psi}$ is defined by

$$\tilde{\psi} = i\bar{\psi}\gamma^0,$$

(2.8)

where the notation on the right-hand side automatically implies that now $\bar{\psi}$ has to be understood as a row, since $\gamma^0$ acts from the right.

The meaning of symbols may depend on the section where they are used, e.g. the symbols $\|\cdot\|$ resp. $\|\cdot\|_1$ denote different norms, though their specific definitions will depend on the contexts in which they are used, though $\|\cdot\|$ always denotes a (weighted) $L^2$-norm and $\|\cdot\|_1$ a stronger energy norm.

Let $\Omega \subset \mathbb{R}^n$, $1 \leq n$, be an open set; then we denote by

$$H^{1,2}(\Omega)$$

(2.9)

the usual Sobolev space with the norm

$$\int_{\Omega} \left( |Du|^2 + |u|^2 \right).$$

(2.10)

When $E$ is the Banach space and $\Omega \subset \mathbb{R}^n$ as before, we denote the space of test functions defined in $\Omega$ with values in $E$ by

$$C^\infty_c(\Omega, E).$$

(2.11)

We also use a correction term $\chi_0$ occasionally when defining the Lagrangian, which is a function defined in the space of Lorentz metrics on $N$ such that when $\chi_0$ is evaluated at a metric of the form

$$dx^2 = -w^{-2}(dx^0)^2 + e^{2f} \sigma_{ij} dx^i dx^j,$$

(2.12)

$$\chi_0 = e^{6f},$$

(2.13)

cf [9, lemma 3.1].

3. The strong interaction

The underlying gauge group for the strong interaction is $SU(3)$. We shall consider a general $SU(n)$, $n \geq 2$, instead, since an arbitrary $n$ poses no greater challenges.

As already mentioned in the introduction we have to look at very special gauge fields that reflect the symmetries of the underlying spacetime up to a gauge transformation. When the spacetime is a Friedman–Robertson–Walker space which is topologically either

$$N = \mathbb{R} \times S^3$$

(3.1)

or

$$N = \mathbb{R} \times \mathbb{R}^3,$$

(3.2)
the gauge fields have to be either $SO(4)$ symmetric, i.e. symmetric with respect to both left and right actions of $SU(2) \equiv SO(3)$ on the spacelike sections of $N$, or symmetric with respect to rigid motions in $\mathbb{R}^3$ after an appropriate gauge transformation.

Let the spacetime metric satisfy
\[
d\bar{s}^2 = -w^2 dx^0^2 + e^{i\ell} \sigma_{ij} dx^i dx^j, \tag{3.3}\]
where $(\sigma_{ij})$ is the standard metric of a space of constant curvature $S_0$, at the moment we allow the possibilities $S_0 = S^3$ or $S_0 = \mathbb{R}^3$, but later we shall stipulate $S_0 = \mathbb{R}^3$, and let the left-invariant 1-forms $\omega^a$, $1 \leq a \leq 3$, satisfy
\[
\sigma_{ij} = \delta_{ab} \omega^a_i \omega^b_j \wedge \sigma_{ij} \omega^a_i \omega^b_j = \delta^{ab} \tag{3.4}\]
and
\[
d\omega^a = \begin{cases} 0, & S_0 = \mathbb{R}^3, \\ \frac{1}{2} \epsilon^{abc} \omega^b \wedge \omega^c, & S_0 = S^3. \end{cases} \tag{3.5}\]

Let $E_{km}$ be the matrices
\[
E_{km} = (\delta^k_i \delta^m_j) \tag{3.6}\]
for $1 \leq k, m \leq n + 3$ and set
\[
T_{km} = E_{km} - E_{mk} \tag{3.7}\]
for $1 \leq k \neq m \leq n + 3$.

The $T_{km}$ with $1 \leq k < m \leq 3$ are generators of $\mathfrak{so}(3)$ or equivalently of the Lie algebra of the adjoint representation of $SU(2)$ which is isomorphic to $\mathfrak{su}(2)$. The precise correspondence with the Pauli matrices will be given later in section 6.

We stipulate that the indices $a, b, c$, when used in connection with these generators or with the matrices in (3.6) or (3.7), will always run from 1 to 3.

Following [1] and [13] we define the connection $A = A(t)$ by
\[
A(t) = \hat{A}(t) + B(t), \tag{3.8}\]
where
\[
\hat{A}(t) = \left( A_{km}(t) E_{k+3,m+3} - \frac{1}{2} \Lambda^k_a(t) E^a_m \right) dt, \tag{3.9}\]
\[
B(t) = \left( -\varphi_0 T_{bc} \epsilon^a_b \omega^c + \bar{z}_k^a(t) E_{n,k+3} - \bar{z}_k^a(t) E_{k+3,n} \right) \omega^0_a dx^i, \tag{3.10}\]

$(A_{km}(t))$, $1 \leq k, m \leq n$, is an arbitrary anti-Hermitian matrix, $\varphi_0 = \varphi_0(t)$ is a real function and $\bar{z}_k^a$, $1 \leq k \leq n$, are arbitrary complex-valued functions. The bar indicates complex conjugation.

Writing
\[
A = A_\mu dx^\mu \tag{3.11}\]
the connection $(A_\mu)$ then has values in $\mathfrak{su}(n + 3)$. The connection
\[
\hat{A} = \hat{A}_\mu dx^\mu = \hat{A}_0 dx^0 \tag{3.12}\]
can be viewed as being a general element of $u(n)$, when $\hat{A}_0$ is considered to be a homomorphism in the $n$-dimensional subspace of $\mathbb{C}^{n+3}$ defined by
\[
\{ \xi = (0, 0, 0, \xi^{1+3}, \ldots, \xi^{n+3}) : \xi^{k+3} \in \mathbb{C}, 1 \leq k \leq n \} \equiv \mathbb{C}^n. \tag{3.13}\]

1 In the appendix of this paper the necessary procedures for a spacetime $N = \mathbb{R} \times S_0$ with a general homogeneous space $S_0$ are described.
For convenience we shall label the components of $\zeta$ in the form
\[ \zeta = (0, 0, 0, \zeta^k) \equiv (\zeta^k) \quad (3.14) \]
in this case.

However, we shall consider $\hat{A}_0$ as a general $U(n)$ connection only for $n = 1$. In the case $n \geq 2$ we shall in addition require
\[ A^k_0 = 0 \quad (3.15) \]
such that $A_0$ has values in $su(n)$. $\hat{A} = \hat{A}(t)$ will then be the actual $SU(n)$ connection.

The corresponding matter Lagrangian comprises three terms: the energy of the gauge field
\[ L_{YM} = \frac{1}{4} \mathrm{tr}(F_{\mu\nu}F^{\mu\nu}) \quad (3.16) \]
a Higgs term
\[ L_{H} = -\left( \frac{1}{2} \bar{\Phi}^a \Phi^a - \frac{1}{4} + U(\Phi) \chi \right) \quad (3.17) \]
and a massive Dirac Lagrangian describing the fermionic sector
\[ L_F = -\frac{1}{2} \left\{ \bar{\psi} \gamma^a \mathcal{D}_\mu \psi \right\} - m \bar{\psi} \psi + \frac{1}{6} \left| \bar{\psi} \right|^2 \quad (3.18) \]

**Lemma 3.1.** Let $S_0 = \mathbb{R}^3$ and $A$ be the connection in (3.8); then its energy
\[ F^2 = -\mathrm{tr}(F_{\mu\nu}F^{\mu\nu}) \quad (3.19) \]
can be expressed as
\[ F^2 = -12 \left\{ 2|\bar{\psi}|^2 + \left| \frac{D}{dt} \bar{z} \right|^2 \right\} w^{-2} e^{-2f} + 12 \left\{ \psi_0^4 + 8\bar{\psi}_0^2 |z|^2 + |z|^4 \right\} e^{-4f} \quad (3.20) \]
where, in the case $n \geq 2$,
\[ \frac{D}{dt} \bar{z}^k = \bar{z}^k + A^k_m \bar{z}^m \quad (3.21) \]
and $\Lambda \in su(n)$, while for $n = 1$, $\Lambda \in u(1)$,
\[ \Lambda = \Lambda^{11} = i \vartheta(t), \quad \vartheta(t) \in \mathbb{R} \quad (3.22) \]
and
\[ \frac{D}{dt} z = \dot{z} + \frac{4}{3} i \vartheta \dot{z} \quad (3.23) \]

**Proof.** The proof is straightforward by observing that, when choosing local coordinates such that $\omega_{ij} = \delta_{ij}$,
\[ F_{0j} = -\bar{\phi}_0 \epsilon_{ab} T_{kb} \omega_{ij}^a + \left\{ -\frac{D}{dt} \bar{z}^k E_{k+3,j} + \frac{D}{dt} \bar{z}^m E_{j,m+3} \right\} \quad (3.24) \]
where the different definitions of the covariant derivative of $z$ are due to the fact that, in the case $n \geq 2$, $\Lambda$ has the trace zero.

The other non-vanishing components $F_{ij}$, $i \neq j$, are
\[ F_{ij} = -4\bar{\phi}_0 \epsilon_{ij} \epsilon_{ab} T_{ac} - 4\bar{\phi}_0 \bar{z}^k \epsilon_{ij} \epsilon_{ak} E_{k+3,j} + 4\bar{\phi}_0 \bar{z} \epsilon_{ij} \epsilon_{k+3,c} E_{k+3,c} - |z|^2 T_{ij} \quad (3.25) \]
The final result is then a simple computation. \hfill \square

Let us now look at the Higgs term. The scalar field $\Phi = (\Phi^k)$ has values in $\mathbb{C}^{n+3}$, or effectively in $\mathbb{C}^n$, according to the conventions in (3.13) and (3.14).
The covariant derivative $D_\mu \Phi = \Phi_\mu$ can be defined either by
\[
\Phi_\mu = \Phi,\mu + g_1 A_\mu \Phi
\]  
(3.26) or by
\[
\Phi_\mu = \Phi,\mu + g_1 \hat{A}_\mu \Phi,
\]  
(3.27)
where $g_1$ is a positive coupling constant. Both definitions make sense. In (3.26) we consider the full connection $A$, while in (3.27) only the effective connection $\hat{A} \in su(n)$ resp. $\hat{A} \in u(1)$, when $n = 1$ is taken into account.

Evaluating
\[
|D\Phi|^2 = \bar{g}^{\mu \lambda} \Phi_\mu \Phi_\lambda
\]  
(3.28) in the case of (3.26) we obtain
\[
|D\Phi|^2 = -w^{-2} \left| \frac{D}{dt} \Phi \right|^2 + 2g_1^2 e^{-2f} |\langle \Phi, z \rangle|^2,
\]  
(3.29)
where
\[
\frac{D}{dt} \Phi^k = \Phi^k + g_1 A^k_m \Phi^m
\]  
(3.30)
and
\[
\langle \Phi, z \rangle = \Phi_k \bar{z}^k.
\]  
(3.31)
In the case of (3.27) we have
\[
|D\Phi|^2 = -w^{-2} \left| \frac{D}{dt} \Phi \right|^2,
\]  
(3.32)

The additional lower order term in (3.29) would have the effect that the bosonic Hilbert space, we will be working in after quantization, would no longer be invariant with respect to the corresponding Hamiltonian. Though the overall solvability would not be endangered the lacking invariance suggests that the effective connection will also be the more natural one and we shall always use definition (3.27).

The potential $U = U(\Phi)$ should be of the form
\[
U = U_0(|\Phi|^2)
\]  
(3.33)
with a smooth $U_0$ such that after quantization the resulting Hamiltonian, combining Yang–Mills and Higgs field, is self-adjoint with a complete sequence of eigenvectors having positive eigenvalues.

Requiring the estimate
\[
-c_2 + c_1 |\Phi|^2 p \leq U(\Phi) \leq c'_1 |\Phi|^2 p + c'_2,
\]  
(3.34)
with $1 \leq p \in \mathbb{N}$ and positive constants $c_1, c'_1$ and non-negative constants $c_2, c'_2$, will guarantee a complete set of eigenvectors. However, a finite number of eigenvalues could be negative under this very weak assumptions. A positive lower bound of the eigenvalues can be proved, if either the constant $c_2$ is small relative to $c_1$ or if $U$ satisfies the additional condition
\[
U(\Phi) \geq 0.
\]  
(3.35)
Hence, the potentials
\[
U(\Phi) = \lambda (|\Phi|^2 - \mu)^2,
\]  
(3.36)
$\lambda, \mu \in \mathbb{R}$, $\lambda > 0$, or
\[
U(\Phi) = \lambda |\Phi|^4 + \mu |\Phi|^2
\]  
(3.37)
with \( \lambda > 0 \) and \( \mu \in \mathbb{R} \) satisfying
\[
|\mu| < c_0(\lambda)
\] (3.38)
would lead to positive energy levels, see theorem 9.3. As we have already mentioned in section 2, the energy \(|D\Phi|^2\) as well as the potential \(U\) should be multiplied by appropriate powers of a correction term \(\chi_0\) which will ensure that these terms are equipped with the right powers of the scale factor, cf [9, lemma 3.1] for details.

It turns out that \(|D\Phi|^2\) has to be multiplied by \(\chi^{-1/3}_0\) and \(U\) by \(\chi^{-1}_0\).

Let us summarize these results in

**Lemma 3.2.** Choosing a coordinate system such that the metric \((\tilde{g}_{\mu\nu})\) is expressed as in (3.3); then the Higgs term (3.17) has the form
\[
L_{H_1} = \frac{1}{2} w^{-1} \left| \frac{d\Phi}{dt} \right|^2 e^{-2f} - U(\Phi) e^{-4f}.
\] (3.39)

The Lagrangian of the fermionic field is stated in (3.18). Here, \(\psi = (\psi^a_\mu)\) is a multiplet of spinors with spin \(\frac{1}{2}\); \(a\) is the spinor index, \(1 \leq a \leq 4\), and \(i, 1 \leq i \leq n\), is the colour index, where we use the convention expressed in (3.14), namely
\[
\psi = (0, 0, 0, \psi^a_\mu) \equiv (\psi^a_\mu).
\] (3.40)

We will also lower or raise the index \(i\) with the help of the Euclidean metric \((\delta_{ij})\).

Let \(\Gamma_\mu\) be the spinor connection
\[
\Gamma_\mu = \frac{1}{4} \omega^{\mu}_{\nu a} \gamma_b \gamma^a;
\] (3.41)
then the covariant derivative \(D_\mu \psi\) is defined by
\[
D_\mu \psi = \psi_{,\mu} + \Gamma_\mu \psi + g_{1} A_{\mu} \psi.
\] (3.42)

In contrast to the previous consideration, when we looked at the Higgs term, we do not have to worry about which connection to take, the full connection \(A_\mu\) or the effective connection \(\hat{A}_\mu\). The Lagrangian will be the same in both cases this time.

Let \((e^b_\lambda)\) be a 4-bein such that
\[
\tilde{g}_{\mu\lambda} = \eta_{ab} e^a_\mu e^b_\lambda,
\] (3.43)
where \((\eta_{ab})\) is the Minkowski metric, and let \((E^a_\mu)\) be its inverse such that
\[
E^a_\mu = \eta_{ab} \tilde{g}^{\mu\lambda} e^b_\lambda,
\] (3.44)
cf [5, p 246].

The covariant derivative of \(E^a_\mu\) with respect to \((\tilde{g}_{\mu\nu})\) is then given by
\[
E^a_{\alpha,\mu} = E^a_{\alpha,\mu} + \Gamma^a_{\mu\alpha} E_\mu^a
\] (3.45)
and
\[
\omega^{\mu}_{\nu a} = E^\lambda_{\alpha,\mu} e^b_\lambda = -E^\lambda_{a,\mu} e^b_\lambda;
\] (3.46)

hence
\[
\Gamma_\mu = \frac{1}{4} \omega^{\mu}_{\nu a} \gamma_b \gamma^a = \frac{1}{4} E^\lambda_{a,\mu} e^b_\lambda \gamma_b \gamma^a = -\frac{1}{4} E^b_{a,\mu} e^b_\lambda \gamma_b \gamma^a.
\] (3.47)

If we choose in (3.14) \(S_0 = \mathbb{R}^3\) and \(\sigma_{ij} = \delta_{ij}\), we deduce
\[
\Gamma_0 = 0
\] (3.48)
and
\[
\Gamma_i = \frac{1}{2} w^{-1} f \ e^i_\gamma \gamma^0, \quad 1 \leq i \leq 3.
\] (3.49)
To simplify the presentation we will consider the connection $\hat{A}$ when calculating the covariant derivatives of $\psi$, since one can easily check that the final result will not be affected by this choice.

Thus we deduce

$$D_{0}\psi = \dot{\psi} + g_{1}\hat{A}_{0}\psi, \quad (3.50)$$

$$D_{k}\psi = \Gamma_{k}\psi = \frac{1}{2}w^{-1}\dot{f}\ e^{f}\gamma_{k}^{0}, \quad (3.51)$$

and

$$\bar{\psi}_{i}E_{a}^{\mu}\gamma^{a}(D_{\mu}\psi)^{i} = \bar{\psi}_{i}i\gamma^{0}\left\{ E_{a}^{\mu}\gamma^{a}D_{0}\psi^{i} + E_{a}^{k}\gamma^{a}D_{k}\psi^{i}\right\}$$
$$= i\bar{\psi}_{i}\gamma^{0}\left\{ w^{-1}\gamma^{0}\left( \psi^{i} + A^{i}_{j}\psi^{j}\right) + e^{-f}\gamma^{k}\frac{1}{2}w^{-1}\dot{f}\ e^{f}\gamma_{k}^{0}\psi^{i}\right\} , \quad (3.52)$$

where we used

$$E_{0}^{a} = w^{-1}\delta_{0}^{a} \cap E_{k}^{a} = e^{-f}\delta_{k}^{a} , \quad (3.53)$$

when $\sigma_{ij} = \delta_{ij}$.  

In view of (2.2) we have

$$\gamma^{k}\chi = 3I \cap \gamma^{0}\gamma^{0} = -I ; \quad (3.54)$$

hence the right-hand side of (3.52) is equal to

$$i\bar{\psi}_{i}\gamma^{0}\left\{ w^{-1}\gamma^{0}\left( \psi^{i} + A^{i}_{j}\psi^{j}\right) + \frac{1}{2}w^{-1}\dot{f}\gamma^{0}\psi^{i}\right\} , \quad (3.55)$$

and we deduce further, by setting

$$\chi = e^{\frac{3}{2}f}\psi , \quad (3.56)$$

$$\bar{\psi}_{i}E_{a}^{\mu}\gamma^{a}(D_{\mu}\psi)^{i} = i\bar{\chi}_{i}\gamma^{0}w^{-1}\gamma^{0}D_{i}\psi^{i}e^{-3f} = -i\bar{\chi}_{i}D_{i}\psi^{i}w^{-1}e^{-3f} , \quad (3.57)$$

where

$$\frac{D}{dt}\chi^{i} = \dot{\chi}^{i} + g_{1}A^{i}_{j}\chi^{j} . \quad (3.58)$$

Summarizing the preceding results we obtain

**Lemma 3.3.** The Dirac Lagrangian can be expressed as

$$L_{F_{i}} = \frac{i}{2}\left( \bar{\chi}_{i}D_{i}\chi^{i} - \frac{D}{dt}\chi^{i}\chi^{i}\right)w^{-1}e^{-3f} - m\bar{\chi}_{i}\gamma^{0}\chi^{i}e^{-3f} , \quad (3.59)$$

in view of the definition of $\chi_{0}$.  

4. Quantization of the Lagrangian

We consider the functional

$$J = \alpha_{M}^{-1}\int_{\Omega}(\bar{R} - 2\Lambda) + \int_{\Omega}\frac{1}{4}\text{tr}(F_{\mu\lambda}F^{\mu\lambda}) - \int_{\Omega}\left\{ \frac{1}{2}\bar{\psi}_{i}\gamma^{0}(D_{\mu}\psi)^{i} + \bar{\psi}_{i}E_{a}^{\mu}\gamma^{a}(D_{\mu}\psi)^{i} - m\bar{\psi}_{i}\gamma^{0}\chi^{i}\right\}$$
$$+ \int_{\Omega}\left\{ \frac{1}{2}\bar{\psi}_{i}E_{a}^{\mu}\gamma^{a}(D_{\mu}\psi)^{i} + \bar{\psi}_{i}E_{a}^{\mu}\gamma^{a}(D_{\mu}\psi)^{i} - m\bar{\psi}_{i}\gamma^{0}\chi^{i}\right\} , \quad (4.1)$$

where $\alpha_{M}$ is a positive coupling constant, and $\Omega \subset N$ is open such that

$$\Omega = I \times \bar{\Omega} ; \quad (4.2)$$
$I = (a, b)$ is a bounded interval and $\Omega \subset S_0 = \mathbb{R}^3$ an arbitrary open set of measured one with respect to the standard metric of $\mathbb{R}^3$.

We use the action principle that, for an arbitrary $\Omega$ as described above, a solution $(A, \Phi, \psi, \bar{g})$ should be a stationary point of the functional with respect to compact variations. This principle requires no additional surface terms for the functional.

Using lemmas 3.1–3.3 and arguing as in [10, section 3], where we observe that now $\bar{\kappa} = 0$, we conclude that the functional is equal to

$$J = \alpha_{\mu}^{-1} \int_a^b \left\{ (-6 f |f|^2 e^{3f} w^{-1} - 2 \Lambda e^{3f} w \right\}
+ 3 \int_a^b \left\{ \left( 2 |\psi_0| \right)^2 + \left| \frac{D}{dt} \bar{z} \right|^2 \right\} e^{3f} w^{-1} - (\psi_0^2 + 8 \psi_0^2 |z|^2 + |z|^4) w e^{-f}
+ \int_a^b \left\{ \frac{1}{2} \left| \frac{D}{dt} \Phi \right|^2 e^{f} - U w e^{-f} \right\}
+ \int_a^b \left\{ \frac{i}{2} \left\{ \frac{D}{dt} \chi_i - \frac{D}{dt} \chi^i \chi_i \right\} - mi \bar{\chi}_i \chi^0 \chi^i w e^{-f} \right\}. \quad (4.3)$$

Here a dot indicates differentiation with respect to the time $t = x^0$ and the covariant derivatives $\frac{D}{dt}$ of the variables $z, \Phi, \chi$ are defined in (3.21), (3.23), (3.30) and (3.58).

Thus, our functional depends on the variables $(f, \psi_0, z^i, \Phi^i, \chi^i, w, \Lambda^i_j)$. For the variables $w$ and $\Lambda^i_j$ no time derivatives exist, i.e. the Legendre transformation will be singular resulting in corresponding constraints. In the case of $w$ we obtain the well-known Hamiltonian constraint, while in the case of the $\Lambda^i_j$ the constraint equations are a bit more complicated. We shall address this issue later.

The dynamical variables are $(f, \psi_0, z^i, \Phi^i, \chi^i)$, where $z^i, \Phi^i$ are complex and $\chi^i$ are anticommuting Grassmann variables. Therefore, we assume that the bosonic and fermionic variables are elements of a graded Grassmann algebra with involution, where the bosonic variables are even and the fermionic variables are odd. The involution corresponds to the complex conjugation and will be denoted by a bar.

The $\chi^i$ are complex variables and we define its real resp. imaginary parts as

$$\xi_a^i = \frac{1}{\sqrt{2}} (\chi^a + \bar{\chi}_a^i) \quad (4.4)$$
resp.

$$\eta_a^i = \frac{1}{\sqrt{2i}} (\chi^a - \bar{\chi}_a^i). \quad (4.5)$$

Then,

$$\chi_a^i = \frac{1}{\sqrt{2}} (\xi_a^i + i \eta_a^i) \quad (4.6)$$

and

$$\bar{\chi}_a^i = \frac{1}{\sqrt{2}} (\xi_a^i - i \eta_a^i). \quad (4.7)$$

In the case of even variables we use the usual definitions

$$z^i = x^i + iy^i. \quad (4.8)$$

With these definitions we obtain

$$\frac{i}{2} \left( \frac{D}{dt} \chi_i - \frac{D}{dt} \chi^i \chi_i \right) = \frac{i}{2} \left( \xi_a^i \frac{D}{dt} \xi_a^i + \eta_a^i \frac{D}{dt} \eta_a^i \right). \quad (4.9)$$
Casalbuoni quantized a Bose–Fermi system in [3, section 4] the results of which can be applied to spin $\frac{1}{2}$ fermions. The Lagrangian in [3] is the same as our Lagrangian in (4.9), and the left derivative is used in that paper; hence we are using left derivatives as well such that the conjugate momenta of the odd variables are, e.g.,

$$\pi_i^a = \frac{\partial L}{\partial \dot{\xi}_i^a} = -\frac{i}{2} \xi_i^a,$$

and thus the conclusions in [3] can be applied.

The Lagrangian has been expressed in real variables—at least the important part of it—and it follows that the odd variables $\xi_i^a, \eta_i^a$ satisfy, after introducing anticommutative Dirac brackets as in [3, equation (4.11)],

$$\{\xi_i^a, \xi_j^b\}_+ = -i\delta^{ij}\delta_{ab}, \quad (4.11)$$

$$\{\eta_i^a, \eta_j^b\}_+ = -i\delta^{ij}\delta_{ab}, \quad (4.12)$$

and

$$\{\xi_i^a, \eta_j^b\}_+ = 0, \quad (4.13)$$

cf [3, equation (4.19)].

In view of (4.6), (4.7) we then derive

$$\{\chi_i^a, \bar{\chi}_j^b\}_+ = -i\delta^{ij}\delta_{ab}. \quad (4.14)$$

Canonical quantization—with $\hbar = 1$—then requires that the corresponding operators $\hat{\chi}_i^a, \hat{\bar{\chi}}_j^b$ satisfy the anticommutative rules

$$[\hat{\chi}_i^a, \hat{\bar{\chi}}_j^b]_+ = i\{\chi_i^a, \bar{\chi}_j^b\}_+ = \delta^{ij}\delta_{ab} \quad (4.15)$$

and

$$[\hat{\chi}_i^a, \hat{\chi}_j^b]_+ = [\hat{\bar{\chi}}_i^a, \hat{\bar{\chi}}_j^b]_+ = 0, \quad (4.16)$$

cf [2, equation (3.10)] and [3, equation (4.17)].

We could then define a finite-dimensional Hilbert space, using Berezin integration, where these operators would be acting, this is done e.g. in [14, page 1494], or we could observe, writing $\chi_i^a$ for $\hat{\chi}_i^a$, etc, that $\chi_i^a$ resp. $\bar{\chi}_i^a$ can be looked at as being annihilation resp. creation operators in the antisymmetric Fock space, cf [4, chapter 65]; note that Dirac used the reversed symbols for the annihilation and creation operators.

We adopt the view to represent the operators as operators in the antisymmetric Fock space. Let $\eta_0$ be the vacuum vector, normalized to $\|\eta_0\| = 1$; then the vector space, where the operators are acting, is spanned by $\eta_0$ and by

$$\hat{\chi}_i^a \hat{\chi}_j^b \cdots \hat{\chi}_r^b \eta_0, \quad (4.17)$$

$$\hat{\bar{\chi}}_i^a \hat{\chi}_a^i \cdots \hat{\bar{\chi}}_r^c \eta_0, \quad (4.18)$$

and mixed products

$$\hat{\chi}_i^a \hat{\chi}_j^b \cdots \hat{\bar{\chi}}_r^c \eta_0, \quad (4.19)$$

where all operators acting on $\eta_0$ have to be different; otherwise the result will vanish. Hence, the vector space is a finite-dimensional subspace of the antisymmetric Fock space.

Defining the number operator

$$n_i^a = \hat{\chi}_i^a \hat{\chi}_i^a, \quad (4.20)$$
we deduce from (4.15)
\[ \chi_i^a \bar{\chi}^a_i = I - n^a_i. \] (4.21)

The vacuum vector \( \eta_0 \) belongs to the kernel of all \( n^a_i \); hence we have
\[ \chi_i^a \bar{\chi}^a_i \eta_0 = \eta_0. \] (4.22)

\( \chi_i^a \) and \( \bar{\chi}^a_i \) are adjoints of each other, i.e. \( n^a_i \) is self-adjoint, and there holds
\[ \chi_i^a \eta_0 = 0 \quad \forall \,(a, i) \] (4.23)
in view of
\[ 0 = n^a_i \eta_0 = \bar{\chi}^a_i \chi_i^a \eta_0. \] (4.24)

Moreover, the vectors in (4.17), (4.18) and (4.19) are normalized eigenvectors of \( n^a_i \) with eigenvalues \( 1 \) resp. \( 0 \) depending on the fact if \( \bar{\chi}^a_i \) happens to be acting on \( \eta_0 \) or not.

The fermionic Hamiltonian is equal to
\[ H_{F_1} = m i \bar{\chi}^a_i \chi^a_i \omega e^{-f}. \] (4.25)

Using the definition of \( \gamma^0 \),
\[ \gamma^0 = i \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix}, \] (4.26)
we deduce
\[ i \bar{\chi}^a_i \gamma^0 i = -\bar{\chi}^a_i \chi^a_i - \bar{\chi}^a_i \chi^a_i, \] (4.27)
where
\[ 1 \leq a \leq 2 \land 3 \leq \bar{a} \leq 4 \] (4.28)
with similar definitions for \( \bar{b}, b, \) etc.

Hence, we conclude
\[ H_{F_1} = m \left( \bar{\chi}^a_i \chi^a_i - \bar{\chi}^a_i \chi^a_i \right) \omega e^{-f}. \] (4.29)

where of course the factor \( \omega e^{-f} \) will be taken care of when we shall consider the full Hamiltonian and the Hamiltonian constraint resp. the Wheeler–DeWitt equation. Note that the sign of \( m \) is irrelevant for our considerations. However, for definiteness, we shall assume \( m > 0 \).

Let us now quantize the bosonic part. Without changing the notation we shall assume that the complex fields \( \Phi, z \) have real-valued components by doubling their dimensions; i.e. \( \Phi \) and \( \zeta \) now have \( 2n \) real components
\[ \Phi = (\Phi^i) \land z = (z^i), \quad 1 \leq i \leq 2n. \] (4.30)

Before we apply the Legendre transformation, let us express the quadratic derivative terms with the help of a common metric.

For \( 0 \leq A, B \leq 4n + 1 \), define
\[ (\gamma^A) = (f, \psi_0, z^i, \Phi^i), \] (4.31)
\[ (G_{AB}) = \text{diag}(-12\alpha^{-1}e^{2f}, 12, 6I_{2n}, I_{2n})e^{f}. \] (4.32)

and
\[ V = 3(\psi_0^2 + 8\psi_0^2|z|^2 + |z|^4). \] (4.33)
Then \( J \) in (4.3) can be expressed as
\[
J = \int_a^b \left\{ \frac{G_{AB}}{\text{d}t} \frac{\text{d}}{\text{d}t} y^A y^B w^{-2} - 2\alpha \Lambda e^f - V e^{-f} - U e^{-f} \right\} + \int_a^b \left\{ \frac{i}{2} \left( \tilde{\chi}^a_{\mu} \frac{\text{d}}{\text{d}t} \chi^a_{\mu} - \frac{\text{d}}{\text{d}t} \chi^a_{\mu} \chi^a_{\mu} \right) - m (\tilde{\chi}^a_{\mu} \chi^a_{\mu} - \tilde{\chi}^a_{\mu} \chi^a_{\mu}) e^{-f} w \right\}. 
\]
(4.34)

Applying now the Legendre transformation we obtain the Hamiltonian
\[
\tilde{H} = \tilde{H}(w, y^A, \chi^a_{\mu}, \eta^a_{\mu}, p_A) = p_A \frac{\text{d}}{\text{d}t} y^A + \pi^a_{\mu} \frac{\text{d}}{\text{d}t} \xi^a_{\mu} + \sigma^a_{\mu} \frac{\text{d}}{\text{d}t} \eta^a_{\mu} - L \\
= \left\{ \frac{1}{2} G_{AB} \frac{\text{d}}{\text{d}t} y^A \frac{\text{d}}{\text{d}t} y^B w^{-2} + 2\alpha \Lambda e^f + V e^{-f} + U e^{-f} \right\} w + m (\tilde{\chi}^a_{\mu} \chi^a_{\mu} - \tilde{\chi}^a_{\mu} \chi^a_{\mu}) e^{-f} w \\
= \left\{ \frac{1}{2} G_{AB} p_A p_B w^{-2} + 2\alpha \Lambda e^f + V e^{-f} + U e^{-f} \right\} w + m (\tilde{\chi}^a_{\mu} \chi^a_{\mu} - \tilde{\chi}^a_{\mu} \chi^a_{\mu}) e^{-f} w \\
\equiv H w, 
\]
(4.35)

and the Hamiltonian constraint requires
\[
H(y^A, \chi^a_{\mu}, \eta^a_{\mu}, p_A) = 0. 
\]
(4.36)

Canonical quantization stipulates that, in the case of the bosonic variables, we replace the momenta \( p_A \) by
\[
p_A = -i \frac{\partial}{\partial y^A},
\]
(4.37)

where \( \hbar = 1 \), and for the fermionic variables we consider \( \tilde{\chi}^a_{\mu} \) and \( \chi^a_{\mu} \) as creation resp. annihilation operators in a \( 2^{2n} \)-dimensional subspace \( \mathcal{F}_1 \) of the antisymmetric Fock space as described above.

Thus, the Hamilton operator is equal to
\[
H = -\frac{1}{2} \Delta + (V + U) e^{-f} + 2\alpha \Lambda e^f + m (\tilde{\chi}^a_{\mu} \chi^a_{\mu} - \tilde{\chi}^a_{\mu} \chi^a_{\mu}) e^{-f},
\]
(4.38)

where the metric \( G_{AB} \) is a Lorentz metric; i.e. the bosonic part of \( H \) is hyperbolic.

Ignoring for the moment a crucial first-class constraint we have not considered yet, which is due to the variables \( \Lambda^i_j \), we have to find wavefunctions
\[
\Psi = \Psi(y),
\]
(4.39)

where
\[
\Psi : \mathbb{R}^{4n+2} \rightarrow \mathcal{F}_1, 
\]
(4.40)

such that
\[
H \Psi = 0; 
\]
(4.41)

moreover, we even have to find a spectral resolution of this problem.

We shall consider wavefunctions of the form
\[
\Psi(y) = u(y) \otimes \eta, \quad \eta \in \mathcal{F}_1, 
\]
(4.42)

where \( u \) belongs to a suitable Hilbert space consisting of complex-valued functions.

Let \( \Psi = u \otimes \eta \) be a smooth functions; then
\[
\Delta \Psi = \frac{1}{\sqrt{|G|}} \frac{\partial}{\partial y^A} (\sqrt{|G|} G^{AB} \Psi_B).
\]
(4.43)
Now,
\[ |G| = 864\alpha^{-1} e^{4(n+1)f}, \tag{4.44} \]
and hence
\[ -\Delta \Psi = \frac{1}{12} e^{-2(n+1)f} \frac{\partial}{\partial y^0} \left( e^{2(n-1)f} \frac{\partial \Psi}{\partial y^0} \right) - 2a^{ab} \Psi_{ab} e^{-f} - \tilde{\Delta} e^{-f}, \tag{4.45} \]
where \((a^{ab})\) is a positive definite diagonal matrix
\[ (a^{ab}) = \text{diag} \left( \frac{1}{24}, \frac{1}{12}, I_{2n} \right), \tag{4.46} \]
and the indices range from \(1 \leq \alpha, \beta \leq 2n + 1\), and \(\tilde{\Delta}\) is the Laplacian with respect to the \(2n\) variables \(\Phi_i\).

Thus, we deduce from (4.38) that the Wheeler–DeWitt equation looks like
\[ \frac{1}{24} e^{-2(n+1)f} \frac{\partial}{\partial y^0} \left( e^{2(n-1)f} \frac{\partial \Psi}{\partial y^0} \right) - a^{ab} \Psi_{ab} e^{-f} - \tilde{\Delta} e^{-f} + (V + U) \Psi e^{-f} + 2a^{-1}_M \Lambda e^{3f} \Psi + m \left( \gamma^a_i \chi^i_a - \gamma^a_i \chi^a_i \right) \Psi e^{-f} = 0. \tag{4.47} \]

Multiplying this equation by \(e^f\) we have proved

**Theorem 4.1.** The Wheeler–DeWitt equation for the functional \(J\) in (4.3) has the form
\[ H_1 \Psi + H_2 \Psi + H_F \Psi - H_0 \Psi = 0, \tag{4.48} \]
where
\[ H_0 \Psi = -\frac{1}{24} e^{-2(n+1)f} \frac{\partial}{\partial y^0} \left( e^{2(n-1)f} \frac{\partial \Psi}{\partial y^0} \right) - 2a^{-1}_M \Lambda e^{4f} \Psi, \tag{4.49} \]
\[ H_1 \Psi = -a^{ab} \Psi_{ab} + V \Psi, \tag{4.50} \]
\[ H_2 \Psi = -\frac{1}{2} \tilde{\Delta} \Psi + U \Psi \tag{4.51} \]
and
\[ H_F \Psi = m \left( \gamma^a_i \chi^i_a - \gamma^a_i \chi^a_i \right) \Psi. \tag{4.52} \]

We emphasize that \(y^0\) and \(f\) denote the same real variable.

Before we can solve the Wheeler–DeWitt equation we still have to formulate and satisfy the first-class constraint resulting from the presence of the variables \(A^i_j\). This will be done in the next section.

5. A first-class constraint

The Lagrangian functional in the previous section contains as non-dynamical variables \(A^i_j\), besides \(w\), which has already been taken care of by the Hamiltonian constraint.

The requirement that the first variation of the functional with respect to compact variations of all variables should vanish leads to a set of constraint equations due to the presence of \(A^i_j\). \((A^i_j)\) is an arbitrary antisymmetric matrix in \(\mathbb{C}^n\) with trace zero if \(n > 1\).

To compute the first variation of \(J\) with respect to \(A^i_j\), we look at the integral in (4.34). Since we also have to differentiate the Dirac term, it is best to rewrite the quadratic form
\[ \frac{1}{2} G_{AB} \frac{D}{dt} x^A \frac{D}{dt} x^B w^{-1} \tag{5.1} \]
in the form
\[ \frac{1}{2} G_{AB} \frac{D}{dt} y^A \frac{D}{dt} y^B w^{-1}, \tag{5.2} \]
where
\[ (y^A) = (f, \varphi_0, \zeta', \xi'), \tag{5.3} \]
\( \z', \xi' \) are complex components and \( \zeta' \) symbolizes \( \Phi_i \).

The terms involved are
\[ \frac{1}{2} G_{AB} \frac{D}{dt} y^A \frac{D}{dt} y^B w^{-1} + \frac{i}{2} \left( \tilde{x} \frac{D}{dt} x^i - \frac{D}{dt} x^i \tilde{x} \right). \tag{5.4} \]

Let us first look at the bosonic term and because of the symmetry it suffices to consider \( z' \).

The independent components of \( (A'_i) \) can be labelled as
\[ A^k_m, \quad 1 \leq k < m \leq n, \tag{5.5} \]
and
\[ A^k_k, \quad 1 \leq k \leq n - 1, \tag{5.6} \]
if \( n > 1 \), no summation over \( k \). Since \( \text{tr}(A'_i) = 0 \), we assume the first \( (n - 1) \) diagonal elements to be independent imaginary variables and
\[ A^n_n = -\sum_{k=1}^{n-1} A^k_k. \tag{5.7} \]

Let us start with a component
\[ A^k_m = a + ib \tag{5.8} \]
for \( 1 \leq k < m \leq n \).

By observing that
\[ p_A = G_{AB} \frac{D}{dt} y^B w^{-1}, \tag{5.9} \]
we deduce that the terms in (5.4) involving the numbers \( a, b \) are
\[ \frac{1}{2} \left\{ p_k \bar{A}_m^k z^m + p_m A_k^m z^k + \bar{p}_k \bar{A}_m^k \bar{z}^k + \bar{p}_m A_k^m \bar{z}^k \right\}, \tag{5.10} \]
or equivalently,
\[ \frac{1}{2} \left\{ p_k (a - ib) \bar{z}^m - p_m (a + ib) \bar{z}^k + \bar{p}_k (a + ib) z^m - \bar{p}_m (a - ib) z^k \right\}. \tag{5.11} \]

Differentiating first with respect to \( \frac{\partial}{\partial a} \) we obtain
\[ \frac{1}{2} \left\{ \bar{p}_k z^m - p_m z^k \right\} + \frac{1}{2} \left\{ -\bar{p}_m z^k + p_k z^m \right\}, \tag{5.12} \]
and differentiating with respect to \( -\frac{\bar{p}}{\bar{m}} \) yields
\[ \frac{1}{2} \left\{ p_k \bar{z}^m - \bar{p}_m \bar{z}^k \right\} - \frac{1}{2} \left\{ -\bar{p}_m \bar{z}^k + p_k \bar{z}^m \right\}. \tag{5.13} \]

Differentiating the diagonal terms we obtain
\[ \frac{1}{2} \left\{ \bar{p}_n z^n - p_n \bar{z}^n \right\} - \frac{1}{2} \left\{ -\bar{p}_n \bar{z}^n + p_n z^n \right\} \tag{5.14} \]
for \( 1 \leq k \leq n - 1 \), and
\[ \frac{1}{2} \left\{ \bar{p} \bar{z} - p z \right\}, \tag{5.15} \]
in the case \( n = 1 \).
Looking at the terms in (5.12) and (5.13) we see that they represent the real resp. imaginary part of the complex term
\[ \bar{p}_k z^m - p_m z^k, \quad 1 \leq k < m \leq n, \] (5.16)

Note that the variables are still complex Grassmann variables and not yet operators.

When formulating the constraint equations, the terms in (5.12), (5.13) will be set to vanish. Hence, these equations are equivalent to the complex equations
\[ \bar{p}_k z^m - p_m z^k = 0, \quad 1 \leq k < m \leq n, \] (5.17)
as well as to their complex conjugates
\[ p_k \bar{z}^m - \bar{p}_m z^k = 0, \quad 1 \leq k < m \leq n. \] (5.18)

**Remark 5.1.** After quantization the left-hand sides of the equations above will be linear operators in a space of complex-valued test functions. It will turn out that the operator resulting from (5.18) will be the adjoint of the operator resulting from (5.17), what is already evident since the quantization process will turn complex conjugation into forming the adjoint.

Similar arguments apply when we differentiate the Dirac terms. The terms in (5.12) resp. (5.13) will then correspond to
\[ i g_1 \{ \bar{\chi}_k^a \chi_m^a - \bar{\chi}_m^a \chi_k^a \} \] (5.19)
resp.
\[ i g_1 \{ \bar{\chi}_k^a \chi_m^a + \bar{\chi}_m^a \chi_k^a \}, \] (5.20)
hence, the equivalent to (5.17) will be
\[ 2ig_1 \bar{\chi}_k^a \chi_m^a, \] (5.21)
and the equivalent to (5.18)
\[ -2ig_1 \bar{\chi}_m^a \chi_k^a. \] (5.22)

The diagonal term has the form
\[ ig_1 \{ \bar{\chi}_k^a \chi_k^a - \bar{\chi}_n^a \chi_n^a \}, \quad 1 \leq k < n, \] (5.23)
where the summation convention is not used for the index \( k \), but of course for the index \( a \). In the case \( n = 1 \) we have
\[ ig_1 \bar{\chi}_k^a \chi_a. \] (5.24)

Since we shall later, after quantization, when these terms have turned into operators, apply the operators to complex-valued wavefunctions, we consider the complex expressions as the primary terms to determine the constraints.

The full constraint equations are
\[ l_{k,m} + g_1 \bar{l}_{k,m} + g_1 \bar{l}_{k,m} = 0, \quad 1 \leq k < m \leq n, \] (5.25)
or equivalently, their complex conjugates,
\[ \bar{l}_{k,m} + g_1 \bar{l}_{k,m} + g_1 \bar{l}_{k,m} = 0, \quad 1 \leq k < m \leq n, \] (5.26)
\[ l_k + g_1 l_k + g_1 l_k = 0, \quad 1 \leq k < n, \] (5.27)
and
\[ l_0 + g_1 l_0 + g_1 l_0 = 0, \quad n = 1, \] (5.28)
where \( l_{k,m}, l_k \) resp. \( l_0 \) represent the terms in (5.17), (5.14) resp. (5.15), \( \tilde{l}_{k,m}, \tilde{l}_k \) resp. \( \tilde{l}_0 \) are defined by equations (5.21), (5.23) resp. (5.24), while

\[
\tilde{l}_{k,m} = \{ \bar{\pi}_k \zeta^m - \pi_m \bar{\zeta}_k \}. 
\]

(5.29)

\[
\tilde{l}_k = \frac{1}{2} \{ \bar{\pi}_k \zeta^k - \pi_k \bar{\zeta}_k \} - \frac{1}{2} \{ \bar{\pi}_n \zeta^n - \pi_n \bar{\zeta}_n \}. 
\]

(5.30)

and

\[
\tilde{l}_0 = \frac{1}{2} [ \bar{\pi} \xi - \pi \bar{\xi} ] \chi. 
\]

(5.31)

The coupling constant \( g_1 \) appears because it entered into the definition of the covariant derivatives of \( \Phi \) and \( \chi \), but not in the case of \( z \).

The constraint equations are first-class constraints, according to Dirac, and after quantization they have to be satisfied by the wavefunctions.

The terms for the fermionic variables can already be looked at as operators in the antisymmetric Fock space. For the quantization of the bosonic terms, we only consider \( l_{k,m}, l_k \) and \( l_0 \). Writing

\[
p_k = p_{x^k} + i p_{y^k}. 
\]

(5.32)

and

\[
\bar{p}_k = p_{x^k} - i p_{y^k}. 
\]

(5.33)

and replacing \( p_k, \bar{p}_k \) by the operators

\[
p_k \rightarrow -i \left\{ \frac{\partial}{\partial x^k} + i \frac{\partial}{\partial y^k} \right\}, 
\]

(5.34)

\[
\bar{p}_k \rightarrow -i \left\{ \frac{\partial}{\partial x^k} - i \frac{\partial}{\partial y^k} \right\}. 
\]

(5.35)

we deduce from (5.17), (5.14) and (5.15), without changing the notation,

\[
l_{k,m} = \left( y^k \frac{\partial}{\partial x^m} - x^m \frac{\partial}{\partial y^k} \right) + \left( y^m \frac{\partial}{\partial x^k} - x^k \frac{\partial}{\partial y^m} \right) + i \left\{ \left( \frac{\partial}{\partial x^m} - \frac{\partial}{\partial y^m} \right) + \left( \frac{\partial}{\partial x^k} - \frac{\partial}{\partial y^k} \right) \right\}. 
\]

(5.36)

\[
l_k = \left( x^k \frac{\partial}{\partial y^k} - y^k \frac{\partial}{\partial x^k} \right) - \left( x^m \frac{\partial}{\partial y^m} - y^m \frac{\partial}{\partial x^m} \right), 
\]

(5.37)

and

\[
l_0 = \frac{4}{3} \left( \frac{\partial}{\partial y} - \frac{\partial}{\partial x} \right) + \frac{8}{3} \frac{i}{3}. 
\]

(5.38)

When we use formulation (5.18) instead of (5.17), the operator \( l_{k,m} \) in (5.36) will be replaced by its formal adjoint

\[
l_{k,m}^* = - \left( y^k \frac{\partial}{\partial x^m} - x^m \frac{\partial}{\partial y^k} \right) - \left( y^m \frac{\partial}{\partial x^k} - x^k \frac{\partial}{\partial y^m} \right) + i \left\{ \left( \frac{\partial}{\partial x^m} - \frac{\partial}{\partial y^m} \right) + \left( \frac{\partial}{\partial x^k} - \frac{\partial}{\partial y^k} \right) \right\}. 
\]

(5.39)

The differential operators \( \tilde{l}_{k,m}, \) etc, are similarly defined; we shall denote the corresponding variables by \( \tilde{x}^i \) and \( \tilde{y}^i \), \( 1 \leq i \leq n \).
To solve the Wheeler–DeWitt equation we have to define a Hilbert space generated by wavefunctions $\Psi_1$ satisfying the constraint equations

$$(l_{k,m} + gl_{\tilde{k},m} + g_l\tilde{l}_{k,m})\Psi_1 = 0,$$  \hspace{1cm} (5.40)

or equivalently,

$$(l_{k,m}^* + gl_{\tilde{k},m}^* + g_l\tilde{l}_{k,m}^*)\Psi_1 = 0$$  \hspace{1cm} (5.41)

and

$$(l_k + gl_{\tilde{k}} + g_l\tilde{l}_k)\Psi_1 = 0.$$  \hspace{1cm} (5.42)

In the case $n = 1$,

$$(l_0 + gl_0 + g_l\tilde{l}_0)\Psi_1 = 0.$$  \hspace{1cm} (5.43)

Later we shall define various Hilbert spaces and before defining a Hilbert space we shall deliberately decide which constraint formulation, either (5.25) or (5.26), we shall use at the classical level, where both formulations are equivalent, since it will make an important difference after quantization.

The Hilbert spaces will be tensor products, where, to address the constraint equations, it suffices to restrict our attention to wavefunctions of the form

$$\Psi_1 = u(z, \tilde{z}) \otimes \eta,$$  \hspace{1cm} (5.44)

where $(z, \tilde{z}) \in \mathbb{R}^{4n} = \mathbb{R}^{2n} \times \mathbb{R}^{2n}$ and $\eta$ belongs to the antisymmetric Fock space. Occasionally, we also use the symbol $\xi$ instead of $\tilde{z}$.

To solve the constraint equations, we consider each factor $u$ and $\eta$ separately. $\eta$ belongs to a finite-dimensional subspace $F_1$. Define the linear map

$$\lambda_0 = (l_{k,m})_{1 \leq k < m \leq n} : F_1 \rightarrow F_1^{n(n-1)/2}.$$  \hspace{1cm} (5.45)

Let $F_0$ be the image of

$$F_1 \ni \eta \rightarrow \eta \equiv (\eta, \ldots, \eta) \in F_1^{n-1},$$  \hspace{1cm} (5.46)

and $A_0$ be the map

$$A_0 = (l_k)_{1 \leq k < n} : F_0 \rightarrow F_1^{n-1}.$$  \hspace{1cm} (5.47)

We then look for eigenspaces of $-iA_0$

$$\tilde{F}_\sigma = \{ \eta \in F_0 : -iA_0\eta = \sigma\eta \},$$  \hspace{1cm} (5.48)

where we identify $\eta$ and $(\eta, \ldots, \eta)$; i.e. we especially consider

$$\tilde{F}_\sigma \subset F_1.$$  \hspace{1cm} (5.49)

**Lemma 5.2.** The eigenvalues $\sigma$ of $-iA_0$ belong to the set

$$M_4 = \{-4, -3, \ldots, 0, \ldots, 3, 4\}$$  \hspace{1cm} (5.50)

and each possible eigenvalue is assumed. The $\tilde{F}_\sigma$ are mutually orthogonal.

**Proof.**

(i) The claim that the eigenvalues are elements of $M_4$ will be proved in lemma 5.4.
(ii) In order to prove that every element of $M_4$ is indeed an eigenvalue we shall give a list of eigenvectors belonging to $\tilde{F}_\sigma$ for each $\sigma \in M_4$.

\[ \tilde{\chi}_1^n \cdots \tilde{\chi}_2^n \eta_0 \in F_{-4}, \]
\[ \tilde{\chi}_1^n \tilde{\chi}_2^n \eta_0 \in F_{-3}, \]
\[ \tilde{\chi}_1^n \tilde{\chi}_3 \eta_0 \in F_{-2}, \]
\[ \tilde{\chi}_1^n \eta_0 \in F_{-1}, \]
\[ \eta_0 \in F_0. \]  

(5.51)  
(5.52)  
(5.53)  
(5.54)  
(5.55)

For $1 \leq b \leq 4$ define

\[ \eta_b = \tilde{\chi}_1^n \cdots \tilde{\chi}_b^n \cdots \tilde{\chi}_{n-1} \cdots \tilde{\chi}_n \eta_0; \]

(5.56)  
then

\[ \eta_b \in F_b. \]

(5.57)

Since the eigenvectors are especially eigenvectors of the self-adjoint operator $-i\hat{t}_1$, eigenvectors belonging to different eigenvalues are orthogonal. □

**Lemma 5.3.** Let $\tilde{\chi}_k^a, \chi_k^a, 1 \leq a \leq m_1$, where $k$ is fixed, be creation resp. annihilation operators in the antisymmetric Fock space; then the eigenvalues of

\[ l_k = \tilde{\chi}_k^a \chi_k^a, \]

(5.58)

where we use summation over $a$, belong to the set

\[ M_1 = \{0, 1, \ldots, m_1\}. \]

(5.59)

**Proof.** We use induction with respect to $m_1$. When $m_1 = 1$, this result is due to the fact that a number operator is a projector.

Thus assume that the claim has already been proved for $m_1 < m$ with $m > 1$ and set $m_1 = m$. Let $\lambda$ be an eigenvalue of $l_k$ and $\eta$ an eigenvector. Then we write $\eta$ as

\[ \eta = \eta_1 + \eta_2, \]

(5.60)

where $\eta_1$ can be written in the form

\[ \eta_1 = \tilde{\chi}_k^1 \xi, \]

(5.61)
and $\eta_2$ can be written as a linear combination of standard basis vectors which do not contain the creation operator $\tilde{\chi}_k^1$. Hence, $\eta_2$ belongs to the kernel of $\tilde{\chi}_k^1 \chi_k^1$ and we deduce

\[ \lambda \eta_1 + \lambda \eta_2 = l_k \eta = \eta_1 + \sum_{a=2}^{m} \tilde{\chi}_k^a \chi_k^a \eta. \]

(5.62)

Let $\tilde{\chi}_k^1$ act on both sides of this equation; then

\[ \lambda \tilde{\chi}_k^1 \eta_2 = \sum_{a=2}^{m} \tilde{\chi}_k^a \chi_k^a \tilde{\chi}_k^1 \eta_2 \]

(5.63)
and we conclude either that $0 \leq \lambda \leq m - 1$ or that $\eta_2 = 0$.

Suppose $\eta_2 = 0$; then, in view of (5.62), we obtain

\[ (\lambda - 1) \eta_1 = \sum_{a=2}^{m} \tilde{\chi}_k^a \chi_k^a \eta_1 \]

(5.64)
yielding
\[ 0 \leq \lambda \leq m \]  
(5.65)

because of the induction hypothesis. \( \square \)

**Lemma 5.4.** Let \( \chi^a_k, \bar{\chi}^a_k, \chi^b_n, \bar{\chi}^b_n, 1 \leq a \leq m_1, 1 \leq b \leq m_2, \) where \( k, n, k \neq n, \) are fixed, be creation resp. annihilation operators in the antisymmetric Fock space; then the eigenvalues of
\[ l = \chi^k_a \bar{\chi}^k_a - \chi^b_n \bar{\chi}^b_n, \]  
(5.66)

where we use summation over \( a \) and \( b, \) belong to the set
\[ M_1 = \{-m_2, -m_2 + 1, \ldots, 0, 1, \ldots, m_1\}. \]  
(5.67)

**Proof.** We use induction with respect to \( m_2. \) Actually we only prove it for \( m_2 = 1 \) and refer for the further steps in the induction arguments to the proof of the preceding lemma. Thus, let \( m_2 = 1 \) and let \( \lambda \) be an eigenvalue of \( l \) with eigenvector \( \eta. \) Split \( \eta \) similarly as in (5.60)
\[ \eta = \eta_1 + \eta_2, \]  
(5.68)

where now
\[ \eta_1 = \xi. \]  
(5.69)

Then, we infer
\[ \lambda \eta_1 + \lambda \eta_2 = l \eta = l_k \eta - \eta_1, \]  
(5.70)

and conclude further, as in the proof before,
\[ l_k \eta_2 = \lambda \bar{\chi}^1 \eta_2; \]  
(5.71)

hence, we either have \( 0 \leq \lambda \leq m_1, \) in view of lemma 5.3, or \( \eta_2 = 0. \) The latter would imply, because of (5.70),
\[ l_k \eta_1 = (\lambda + 1) \eta_1, \]  
(5.72)

completing the proof of the lemma. \( \square \)

**Definition 5.5.** Let \( \tilde{\mathcal{F}}_{\sigma} \) be one of the eigenspaces in lemma 5.2; then we define in the case \( \sigma_i \geq 0 \)
\[ F_{\sigma_i} = \{ \eta \in \tilde{\mathcal{F}}_{\sigma} : \hat{l}_{k,m} \eta = 0 \quad \forall \ 1 \leq k < m \leq n \} \]  
(5.73)

and in the case \( \sigma_i < 0 \)
\[ F_{\sigma_i} = \{ \eta \in \tilde{\mathcal{F}}_{\sigma} : \hat{l}_{k,m} \eta = 0 \quad \forall \ 1 \leq k < m \leq n \}. \]  
(5.74)

**Remark 5.6.** The fermions defined in lemma 5.2 which belong to \( \tilde{\mathcal{F}}_{\sigma} \) also belong to \( F_{\sigma}. \) Hence, we have
\[ \dim F_{\sigma_i} \geq 1 \quad \forall \ 1 \leq i \leq 9. \]  
(5.75)

The eigenspace \( F_0, i.e. \sigma_i = 0, \) will be of special importance, since it contains the \( SU(3) \) fermions used in forming the quarks, when \( n = 3, \) as we shall prove

**Lemma 5.7.** Let \( n \geq 2; \) then the dimension of the eigenspace \( F_0 \) is at least 16. It contains the mutually orthogonal unit vectors
\[ \tilde{\chi}^1_M \cdots \tilde{\chi}^n_M \eta_0, \quad \forall \ M \in \mathcal{P}(\{1, 2, 3, 4\}). \]  
(5.76)
where \( \mathcal{P}([1, 2, 3, 4]) \) is the power set of \([1, 2, 3, 4]\), and the operators \( \hat{x}_M^k \) are defined by

\[
\hat{x}_M^k = \begin{cases} 
I, & M = \emptyset, \\
\hat{x}_{a_1}^k \cdots \hat{x}_{a_i}^k, & M = \{a_1, \ldots, a_i\},
\end{cases}
\]

where, for definiteness, the factors in the product are ordered by the standard order of the natural numbers; i.e. in the above definition, we assume

\( a_1 < a_2 < \cdots < a_i, \)

(5.78)

\textbf{Proof.} Easy exercise. \( \square \)

Next, we fix an eigenvalue \( \sigma_i \) with the corresponding eigenspace \( F_{\sigma_i} \), where we emphasize the convention (5.49), and we define a matching bosonic Hilbert space \( \mathcal{H}(\sigma_i) \) such that

\[
l_k,m u = 0 \land \tilde{l}_k,m u = -i \sigma_i u \quad \forall u \in \mathcal{H}(\sigma_i),
\]

(5.79)

and \( 1 \leq q < n \), and such that

\[
l_q u = 0 \land \tilde{l}_q u = -i \sigma_i u \quad \forall u \in \mathcal{H}(\sigma_i),
\]

(5.80)

for all \( 1 \leq k < m \leq n \), if \( \sigma_i \geq 0 \), and

\[
l_k,m^* u = 0 \land \tilde{l}_k,m^* u = 0 \quad \forall u \in \mathcal{H}(\sigma_i),
\]

(5.81)

for all \( 1 \leq k < m \leq n \), if \( \sigma_i < 0 \).

\textbf{Remark 5.8.} The Hilbert spaces

\( \mathcal{H}(\sigma_i) \otimes F_{\sigma_i} \)

(5.82)

would then be mutually orthogonal and its elements would satisfy the constraints.

We shall show that this procedure is always possible; we formulate and prove the result for generic differential operators \( l_{k,m}, l_k \), resp. for \( l_{k,m}^*, l_k^* \), and for \( n \geq 2 \)—the case \( n = 1 \) will be dealt with in section 8.

\textbf{Theorem 5.9.} For any \( r \in \mathbb{N} \) there exists a largest infinite-dimensional subspace

\[
E \subset C_c^\infty(\mathbb{R}^n, \mathbb{C})
\]

(5.83)

such that all \( u \in E \) satisfy

\[
l_{k,m} u = 0 \quad \forall 1 \leq k < m \leq n
\]

and

\[
l_k u = -i \sigma_i u \quad \forall 1 \leq k < n.
\]

Moreover, let \( V(z) = V_0(|z|^2) \) be a smooth potential, \( V_0 \in C^\infty(\mathbb{R}) \); then \( E \) is invariant with respect to the operators

\[
u \to Vu
\]

and

\[
u \to \Delta u.
\]

\textbf{Proof.} We first prove that there exists an infinite-dimensional subspace with the above properties. For any \( \rho \in C_c^\infty(\mathbb{R}) \) the function

\[
\phi = \rho(|z|^2)
\]

(5.88)
satisfies
\[ l_k,m \varphi = 0 \land l_k \varphi = 0. \] (5.89)

Let
\[ u_n = x^n + iy^n; \] (5.90)
then
\[ l_k u_n = -iu_n \quad \forall 1 \leq k < n \] (5.91)
and
\[ l_{k,m} u_n = 0 \quad \forall 1 \leq k < m \leq n. \] (5.92)

Since \( l_k, l_{k,m} \) are linear differential operators of first order, we infer that
\[ u = u_n \] (5.93)
satisfies
\[ l_k u = -iru \quad \forall 1 \leq k < n. \] (5.94)

Let \( \rho \in C^\infty_c(\mathbb{R}) \) be arbitrary and define
\[ v = u \varphi, \quad \varphi = \rho(|z|^2); \] (5.95)
then \( v \) is smooth and
\[ l_k v = -irv \quad \forall 1 \leq k < n, \] (5.96)
as well as
\[ l_{k,m} v = 0. \] (5.97)

Since the support of \( \rho \) is arbitrary, the functions \( v \) in (5.95) generate an infinite-dimensional subspace \( \tilde{E} \subset C^\infty_c(\mathbb{R}^2n, \mathbb{C}) \).

Obviously, \( \tilde{E} \) is invariant with respect to the operator in (5.86). It remains to prove the invariance with respect to the Laplace operator.

An immediately calculation reveals
\[ \Delta u_n = 0, \] (5.98)
\[ \Delta \varphi = 4n\dot{\rho} + 4\dot{\rho} |z|^2, \] (5.99)
\[ D_j u_n D^j \varphi = 2r u_n \ddot{\rho} \] (5.100)

and
\[ \Delta(u_n \varphi) = (4n\dot{\rho} + 4\dot{\rho} |z|^2)u_n + 4ru_n \varphi. \] (5.101)

Thus, \( \tilde{E} \subset C^\infty_c(\mathbb{R}^2n, \mathbb{C}) \) is infinite dimensional and invariant for \( V \) and \( \Delta \), and its elements satisfy the constraint equations. To define a largest subspace with these properties, we consider the family
\[ \mathcal{F} = \{ F \subset C^\infty_c(\mathbb{R}^2n, \mathbb{C}) : F \text{ subspace with the above properties} \}. \] (5.102)
\( \mathcal{F} \neq \emptyset \) and the space generated by
\[ E = \bigcup_{F \in \mathcal{F}} F \] (5.103)
is the largest subspace with these properties as one easily checks, and hence \( E \) is the largest subspace. \( \square \)
Theorem 5.10. For any $r \in \mathbb{N}$ there exists a largest infinite-dimensional subspace

$$E \subset C^\infty_c(\mathbb{R}^{2n}, \mathbb{C})$$

(5.104)

such that all $u \in E$ satisfy

$$l^*_{k,m}u = 0 \quad \forall 1 \leq k < m \leq n$$

(5.105)

and

$$l_ku = i ru \quad \forall 1 \leq k < n.$$  

(5.106)

Moreover, let $V(z) = V_0(|z|^2)$ be a smooth potential, $V_0 \in C^\infty(\mathbb{R})$; then $E$ is invariant with respect to the operators

$$u \mapsto Vu$$

(5.107)

and

$$u \mapsto \Delta u.$$  

(5.108)

Proof. In view of the proof of the preceding theorem it suffices to show that

$$u_n = x^n - iy^n$$

(5.109)

satisfies

$$l_ku_n = iu_n \quad \forall 1 \leq k < n$$

(5.110)

and

$$l^*_{k,m}u_n = 0 \quad \forall 1 \leq k < m \leq n,$$

(5.111)

but these equations follow immediately. □

Remark 5.11. In the preceding two theorems the elements of $E$ are eigenfunctions of $l_k$ with integer eigenvalues, which will suffice for our purposes, since the corresponding eigenvectors of the fermionic operators $\hat{l}_k$ will also have integer eigenvalues. But even in a situation when the possible eigenvalues of the $\hat{l}_k$ would be multiples of a given positive number $\lambda$, we could define a matching bosonic Hilbert space by modifying the definition of the covariant differentiation of the Higgs field. Instead of definition (3.27) we would then define

$$\Phi_{\mu} = \Phi,\mu + \lambda g_1 \hat{A}_{\mu} \Phi.$$  

(5.112)

Remark 5.12. If the potential $V$ depends on additional variables $\xi = (\xi^i), 1 \leq i \leq m,$

$$V = V_0(|z|^2, \xi),$$

(5.113)

which do not enter into the constraint equations, then a largest subspace can be constructed by choosing the test functions $\psi$ in (5.88) to be of the form

$$\psi = \rho(|z|^2, \xi),$$

(5.114)

with

$$\rho \in C^\infty_c(\mathbb{R} \times \mathbb{R}^m, \mathbb{C}).$$

(5.115)

The resulting largest subspace would be part of $C^\infty_c(\mathbb{R}^{2n} \times \mathbb{R}^m, \mathbb{C})$ and invariant with respect to $V$ as well as with respect to the Laplacians $\Delta_{\mathbb{R}^{2n}}$ and $\Delta_{\mathbb{R}^m}$ or any smooth partial differential operator in $C^\infty_c(\mathbb{R}^m, \mathbb{C})$. 

23
6. The electro-weak interaction

The gauge group of the electro-weak interaction is $SU(2) \times U(1)$. To implement the $U(1)$ action we have to use the $SU(n+3)$ model with $n = 1$. As noted in section 3 the $SU(1+3)$ gauge field contains a general $u(1)$ connection.

For the realization of $SU(2)$ we could either use the same method, i.e. looking at the $SU(n+3)$ model with $n = 2$, or use the $su(2)$ Lie subalgebra which is part of the $SU(1+3)$ model as an embedding of $su(2)$ in $su(3)$, or we could simply use the fact that $SU(2)$ is the simply connected twofold cover of $SO(3)$ and employ the corresponding gauge field which is known to be symmetric with respect to rigid motions of $\mathbb{R}^3$.

The $SU(2+3)$ model has the disadvantage of the additional constraint equations, so this model should be avoided when possible. The remaining two possibilities are very similar. We shall choose the independent $so(3)$ realization of $su(2)$, which has already been used to define quantum cosmological models, cf [9, 11].

Let us briefly describe how $so(3)$ can be looked at as the Lie algebra of $Ad(SU(2))$.

Consider the standard generators $T_i$, $1 \leq i \leq 3$, of $so(3)$ viewed as antisymmetric homomorphisms in $\mathbb{R}^3$ such that

$$[T_i, T_j] = i\epsilon_{ijk}T_k. \quad (6.1)$$

Let $g = su(2)$; then a basis of $g$ is given by the Pauli matrices $\sigma_i$, $1 \leq i \leq 3$, satisfying

$$[\sigma_i, \sigma_j] = 2i\epsilon_{ijk}\sigma_k. \quad (6.2)$$

Now, the classical adjoint representation of $SU(2)$ as homomorphisms of $g$ gives just $SO(3)$ and

$$Ad_x \left( \frac{1}{2i} \sigma_k \right) = T_k, \quad (6.3)$$

see e.g. [7, theorem 19.12] and also [6, equation (1.12)].

Note that $Ad_x^{-1}$ is two valued. Thus, let

$$\tilde{A} = \tilde{\psi} T_a \omega_a^\mu dx^\mu \quad (6.4)$$

be an $SO(3)$ connection; then it can be looked at as the adjoint connection of the $SU(2)$ connection

$$B = \tilde{\psi} \frac{1}{2i} \sigma_a \omega_a^\mu dx^\mu, \quad (6.5)$$

where $\omega_a^\mu$ is the form in (3.5) for $S_0 = \mathbb{R}^3$.

These connections can be extended to the spacetime by setting

$$\tilde{A}_0 = B_0 = 0. \quad (6.6)$$

The additional Lagrangian terms which have to be considered in the functional in (4.1) are

$$\int_{\Omega} \left\{ \frac{1}{4} \text{tr}(F_{\mu\lambda} F^{\mu\lambda}) - \frac{1}{2} \beta \gamma_{\alpha\beta} \tilde{g}^{\mu\nu} A^a_\mu A^b_\nu \tilde{\chi}_0^{-\frac{1}{2}} + \frac{1}{4} \text{tr}(\tilde{F}_{\mu\lambda} \tilde{F}^{\mu\lambda}) 
- \frac{1}{2} \left[ L_i E_\mu^{\nu\alpha} D_\nu L_i + \tilde{e}_R E_\mu^{\nu\alpha} D_\nu e_R + \tilde{L}_i E_\mu^{\nu\alpha} D_\nu L_i + \tilde{e}_R E_\mu^{\nu\alpha} D_\nu e_R \right] 
- \frac{1}{2} \tilde{g}^{\mu\nu} D_\mu \tilde{\psi} D_\nu \tilde{\chi}_0^{-\frac{1}{2}} - h_c (\tilde{\psi} \tilde{\psi}_R L^\alpha + \tilde{\psi}_R L^\alpha e_R) \tilde{\chi}_0^{-\frac{1}{2}} - \tilde{U}(\tilde{\psi}) \tilde{\chi}_0^{-\frac{1}{2}} \right\}, \quad (6.7)$$

where

$$\tilde{U}(\tilde{\psi}) = -m_0^2 |\tilde{\psi}|^2 + b_0 |\tilde{\psi}|^4, \quad b_0 > 0. \quad (6.8)$$
\((\tilde{F}_{\mu\lambda})\) is the field strength of the \(SU(2)\) adjoint connection \((\tilde{A}_\mu)\), which we write in the form
\[
\tilde{A}_\mu = A_\mu + \bar{A}_\mu, \tag{6.9}
\]
where \(\bar{A}_\mu\) is the flat connection; hence \(A_\mu = (A^a_\mu)\) is a tensor; \(\gamma_{ab}\) is the Cartan–Killing tensor of the Lie algebra. The corresponding term in the functional represents the mass of the connection: \(\bar{\mu}\) is called the mass of the connection \(\tilde{A}_\mu\), cf [9, page 2].

\((\hat{F}_{\mu\lambda})\) is the field strength of the \(SU(1+3)\) connection. We now denote the connection by \(C\) instead of \(A\) and consequently \(\hat{C}\) will be the effective \(U(1)\) connection.

With respect to the Dirac terms, the Higgs field and the Yukawa terms, we roughly follow the definitions and notations in [6, page 201], see also [15].

From [9, equation (3.15)] we obtain
\[
\frac{1}{2} \text{tr}(\hat{F}_{\mu\lambda} \hat{F}^{\mu\lambda}) - \frac{1}{4} \bar{\mu} \gamma_{ab} g^{\mu\lambda} A^a_\mu A^b_\lambda \chi_0^{-1} = 3\bar{\psi} u e^{-2f} - 3\bar{\psi}^3 e^{-4f} - 3\bar{\psi}^2 e^{-4f}, \tag{6.10}
\]
where we have to set \(\bar{\psi} = \psi, \bar{\kappa} = 0\) and \(\bar{\mu} = -\mu\), when comparing the reference with the present situation.

The value of
\[
\frac{1}{2} \text{tr}(\hat{F}_{\mu\lambda} \hat{F}^{\mu\lambda}) \tag{6.11}
\]
we infer from (3.20) and (3.23), noting that now \(n = 1\).

Before we inspect the Higgs field \(\varphi = (\varphi^1, \varphi^2)\), let us look at the Dirac term. Now, we use a different spinor basis such that
\[
\gamma^0 = \begin{pmatrix} 0 & I \\ I & 0 \end{pmatrix}, \tag{6.12}
\]
and the helicity operator \(\gamma^5\) is represented as
\[
\gamma^5 = -\gamma^0 \gamma^1 \gamma^2 \gamma^3 = i \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix}, \tag{6.13}
\]
i.e. writing a spinor \(\psi\) in the form
\[
\psi = \begin{pmatrix} \chi \\ \eta \end{pmatrix}; \tag{6.14}
\]
then \(\chi = (\chi_\alpha), 1 \leq \alpha \leq 2\), is left handed and \(\eta = (\eta_\beta), 1 \leq \beta \leq 2\), is right handed.

The Dirac terms in (6.7) have to be understood as inserting
\[
L^i \rightarrow \begin{pmatrix} L^i \\ 0 \end{pmatrix}, \quad 1 \leq i \leq 2, \tag{6.15}
\]
and
\[
e_R \rightarrow \begin{pmatrix} 0 \\ e_R \end{pmatrix}, \tag{6.16}
\]
where \(L^i\) and \(e_R\) are Weyl spinors
\[
L^i = (L^i_\alpha) \land e_R = (e_R^\beta). \tag{6.17}
\]
The covariant derivatives of \(L^i\) resp. \(e_R\) are defined by
\[
D_\mu L^i = \nabla_\mu L^i + g_2 B_\mu L^i + \frac{1}{2} g_3 \hat{C}_\mu L^i \tag{6.18}
\]
and
\[
D_\mu e_R = \nabla_\mu e_R + g_3 \hat{C}_\mu e_R, \tag{6.19}
\]
where $g_2, g_3$ are positive coupling constants. Note that whenever $L^i$ or $e_R$ are acted upon by
the Dirac matrices $\gamma^a$, they have to be expressed in the form (6.15) resp. (6.16), while when
acted upon by the Pauli matrices, they are simply Weyl spinors.

The terms

$$\hat{C}_\mu L^i \wedge \hat{C}_\mu e_R$$

are defined by using the convention in (3.13) as well as the remarks following (3.27); hence

$$\hat{C}_k = 0, \quad 1 \leq k \leq 3,$$

and

$$\hat{C}_0 L^i = i \vartheta L^i, \quad \vartheta \in \mathbb{R}.$$ (6.22)

Let us write (6.18) explicitly in terms of

$$\begin{pmatrix} L^i_0 \\ 0 \end{pmatrix} \wedge L^i,$$

(6.23)

$$D_\mu \begin{pmatrix} L^i_0 \\ 0 \end{pmatrix} = \begin{pmatrix} L^i_\mu \\ 0 \end{pmatrix} + \Gamma_\mu \begin{pmatrix} L^i_0 \\ 0 \end{pmatrix} + g_2 \begin{pmatrix} B_\mu L^i_0 \\ 0 \end{pmatrix} + \frac{g_3}{2} \begin{pmatrix} i \vartheta L^i \\ 0 \end{pmatrix},$$

(6.24)

and similarly for $e_R$.

Applying the definitions of $\gamma^0, \gamma^k$ we then deduce, by replacing at the end of the
computation

$$L^i \rightarrow L^i e^{\frac{3}{2} \vartheta/}$$

and

$$e_R \rightarrow e_R e^{\frac{3}{2} \vartheta/}$$

(6.25)

(6.26)

without changing the notation,

$$\bar{L}^i E^\mu_a \gamma^a D_\mu L^i = -i L^a_\mu \frac{D}{dt} L^i a w^{-1} e^{-3\vartheta} + \frac{3}{2} g_3 \bar{\psi} L^a L^i e^{-4\vartheta}$$

(6.27)

and

$$\bar{e}_R E^\mu_a \gamma^a D_\mu e_R = -i \bar{e}_R \frac{D}{dt} e_R w^{-1} e^{-3\vartheta},$$

(6.28)

where

$$\frac{D}{dt} L^i a = L^a_\mu \mu + \frac{g_3}{2} i \vartheta L^i a$$

(6.29)

and

$$\frac{D}{dt} e_R = \dot{e}_R + g_3 i \vartheta e_R.$$

(6.30)

Let us now consider the Higgs field $\varphi = (\varphi^i(t)), 1 \leq i \leq 2$. Its covariant derivative is
defined by

$$D_\mu \varphi = \varphi_{,\mu} + g_3 B_\mu \varphi + \frac{g_3}{2} \hat{C}_\mu \varphi;$$

(6.31)

hence

$$D_0 \varphi = \dot{\varphi} + \frac{g_3}{2} i \vartheta \varphi,$$

(6.32)

$$D_\lambda \varphi = -i g_3 \frac{\varphi}{2} \sigma_\lambda \varphi$$

(6.33)
and
\[ -\frac{1}{2}g^{\mu\lambda} D_\mu \varphi D_\lambda \varphi = \frac{1}{2} w^{-2} \frac{D}{dt} \varphi - \frac{3}{2} \bar{\varphi} \varphi^2 \varphi^2 e^{-2f}. \quad (6.34) \]

Writing the complex functions \( \varphi^i \) as
\[ \varphi^i = a^i + ib^i, \quad (6.35) \]
we infer
\[ \bar{\varphi}^i \bar{e}_R a^i + \varphi^i \bar{e}_R b^i = -a_i (\bar{e}_R a^i + \bar{e}_R b^i); \quad (6.36) \]

hence, after quantization, it will be a self-adjoint operator in the finite-dimensional Hilbert space generated by the fermions. However, the operator will depend on the spatial variables \( a_i, b_i \), which will turn out to have very important consequences.

Note that a similar term appears on the right-hand side of (6.27), i.e. even without the Yukawa term there would be a self-adjoint operator in the antisymmetric Fock space depending on the spatial variables—for the consequences we refer to remark 11.5.

The constants \( g^2, g^3, b_0 \) and \( h \) are assumed to be positive, while \( m_1 \) may be real or imaginary. Note that the sign of \( h \) is irrelevant.

7. Quantization of the full Lagrangian

Adding the terms in (6.7) to the functional \( J \) in (4.1) and following the procedures in section 4 we arrive at an analogue of equation (4.34) which reads
\[ J = \int_a^b w \left\{ G_{AB} \frac{D}{dt} y_A \frac{D}{dt} y_B w^{-2} - 2\alpha_{\bar{A}} A e^{-2f} - V e^{-f} - U e^{-f} \right\} \]
\[ - \left( 3\bar{\varphi} \varphi^2 + \frac{3}{2} \bar{\varphi} \varphi^2 \varphi^2 + \frac{2}{3} \bar{\varphi} \varphi^2 \varphi^2 \right) e^{-f} \}
\[ + \int_a^b \left\{ \frac{i}{2} \left( \bar{\chi}^a \frac{D}{dt} \chi^a + \bar{\tilde{L}}^a \frac{D}{dt} \tilde{L}^a + \bar{\tilde{e}}^a \frac{D}{dt} \tilde{e}^a \right) + c.c. - m (\bar{\chi}^a \chi^a - \tilde{z}^a \tilde{z}^a) e^{-f} w \]
\[ - h_i (\bar{\tilde{e}}_{Ra} \tilde{L}^{ia} + \tilde{L}^{ia} e_{Ra}) + b_i (-i \bar{\tilde{e}}_{Ra} \tilde{L}^{ia} + i \tilde{L}^{ia} e_{Ra}) e^{-f} w \right\}, \quad (7.1) \]
where
\[ \bar{V} = \bar{\varphi} \varphi^2 + 8\bar{\varphi} \varphi^2 |\tilde{z}|^2 + |\tilde{z}|^4, \quad (7.2) \]
\[ \tilde{z} \in \mathbb{C}, \text{ is the potential coming from the energy of the connection} \ C_\mu, \text{ and where} \]
\[ G_{AB} \frac{D}{dt} y_A \frac{D}{dt} y_B \quad (7.3) \]
has now been modified to incorporate the new variables. Note also that the covariant derivative \( \frac{D}{dt} \) is defined differently depending on the variables it is applied to.

The variable \( y = (y^A) \) is now defined by
\[ y^A = (f, \bar{\psi}_0, \bar{\varphi}, \psi^0, \varphi^0, \varphi^0, \bar{\varphi}_0, \varphi_0^0, \varphi_0^0, \varphi_0^0, \varphi_0^0, \varphi_0^0). \quad (7.4) \]
The additional variables are the real variables \( \bar{\varphi}, \varphi_0, \) the complex variable \( \tilde{z} \) and
\[ \varphi = (\varphi^i) \in \mathbb{C}^2. \quad (7.5) \]
Let us summarize the definitions of the covariant derivatives for the additional variables
\[ \frac{D}{dt} \tilde{z} = \tilde{z}, + \frac{4}{3} i \partial \tilde{z}, \quad (7.6) \]
cf (3.23),
\[
\frac{D}{dt} \varphi = \dot{\varphi} + \frac{g_3}{2} \theta \varphi,
\]
and
\[
\frac{D}{dt} L^i_a = \dot{L}^i_a + \frac{g_3}{2} \theta L^i_a,
\]
and
\[
\frac{D}{dt} e_R^a = \dot{e}_R^a + g_3 \theta e_R^a.
\]

The metric \((G_{AB})\) is the diagonal Lorentz metric
\[
(G_{AB}) = \text{diag}(-\alpha^{-1} e^{2f}, 12, 6I_{2n}, 6, 12, 6I_2, I_4) e^f.
\]

Canonical quantization then leads to the Wheeler–DeWitt equation
\[
H \Psi = 0,
\]
where the Hamilton operator \(H\) is defined by
\[
e^f H = -\frac{1}{2} e^f \Delta + 2\alpha^{-1} e^f + V + U + \bar{V} + \bar{U}
+ (3\dot{\varphi}^2 + 3\dot{\bar{\varphi}}^2 + \frac{3}{2} g_2 \bar{\varphi}^2 |\varphi|^2) + \frac{3}{2} g_2 \bar{\varphi} L^i_a L^i_a + m \left( \chi^i_a \chi^i_a - \bar{\chi}^i_a \bar{\chi}^i_a \right)
+ h_c (a_i (\bar{e}_R^a L^i_a + L^i_a e_R^a) + b_i (-i \bar{e}_R^a L^i_a + i \bar{L}^i_a e_R^a)),
\]
and the Laplace operator with respect to the metric \((G_{AB})\) can be expressed as
\[
-e^f \Delta \Psi = \frac{\alpha M}{12} e^{-2\alpha \frac{5}{2} f} \frac{\partial}{\partial y^0} \left( e^{2\alpha \frac{3}{2} f} \frac{\partial \Psi}{\partial y^0} \right) - 2\alpha^{-1} e^f \Psi,
\]
where
\[
(a^{\alpha \beta}) = \text{diag} \left( \frac{1}{24}, \frac{1}{12} I_{2n}, \frac{1}{2} I_{2n}, \frac{1}{12} \frac{1}{2} I_{2n}, \frac{1}{2} \frac{1}{2} I_{2n}, \frac{1}{2} \frac{1}{2} I_{2n}, \frac{1}{2} \frac{1}{2} I_{2n}, \frac{1}{2} I_4 \right).
\]

Replacing \(e^f H\) by \(H\) without changing the notation, we then have
\[
H = H_1 - H_0,
\]
where
\[
H_0 \Psi = -\frac{\alpha M}{24} e^{-2\alpha \frac{5}{2} f} \frac{\partial}{\partial y^0} \left( e^{2\alpha \frac{3}{2} f} \frac{\partial \Psi}{\partial y^0} \right) - 2\alpha^{-1} e^f \Psi
\]
and
\[
H_1 \Psi = -a^{\alpha \beta} \Psi_{\alpha \beta} + (V + U + \bar{V} + \bar{U}) \Psi + (3\dot{\varphi}^2 + 3\dot{\bar{\varphi}}^2 + \frac{3}{2} g_2 \bar{\varphi}^2 |\varphi|^2) \Psi
+ m \left( \chi^i_a \chi^i_a - \bar{\chi}^i_a \bar{\chi}^i_a \right) \Psi + \frac{3}{2} g_2 \bar{\varphi} L^i_a L^i_a \Psi
+ h_c (a_i (\bar{e}_R^a L^i_a + L^i_a e_R^a) + b_i (-i \bar{e}_R^a L^i_a + i \bar{L}^i_a e_R^a)) \Psi.
\]

Note that the symbols \(f, \varphi_0, z^i, \Phi^i, \bar{\varphi}, \bar{\varphi}_0, \bar{z}^i, \bar{\varphi}^i\) now are variables of the Euclidean space
\[
\mathbb{R} \times \mathbb{R}^{4n+9},
\]
where \(f\) corresponds to the first factor. The complex variables have been expressed by their real and imaginary parts respectively, e.g.
\[
\varphi_a = a_k + i b_k.
\]

The terms in the last two rows of the right-hand side of (7.17) represent a symmetric operator in the finite-dimensional Hilbert space generated by the fermions which also depends on the spatial variables \(a_k, b_k \) and \( \bar{\varphi} \).
Let us write this operator in the form
\[ B + C, \] (7.20)
where \( B \) acts on the fermions from the \( SU(n) \) model and \( C \) on those from the \( SU(2) \times U(1) \) model, and let us abbreviate the rest of the right-hand side by \( A \) such that
\[ H_1 = A + B + C. \] (7.21)
In the next section we shall define the Hilbert space in which \( H_1 \) acts as a symmetric operator.

8. The vector space defined by the constraints of the electro-weak interaction

The functional in (7.1) contains \( \vartheta \) as a non-dynamical variable; hence an additional constraint equation has to be satisfied. Equations (7.6)–(7.9) reveal how \( \vartheta \) enters into the Lagrangian.

Writing \( \hat{z} \) resp. \( \varphi^i \) in the form
\[ \hat{z} = \hat{x} + i \hat{y} \] (8.1)
resp.
\[ \varphi^i = \xi^i + i \eta^i \] (8.2)
for \( 1 \leq i \leq 2 \), we deduce from (5.38) that the differential operator—we now use the notations \( \lambda_0, \tilde{\lambda}_0 \) and \( \hat{\lambda}_0 \)—has the form
\[ \lambda_0 = \frac{4}{3} \left( \hat{x} \frac{\partial}{\partial \hat{y}} - \hat{y} \frac{\partial}{\partial \hat{x}} \right) + i \frac{8}{3}, \] (8.3)
and a variant of (5.38) is also valid for \( \varphi^i \), namely
\[ g_3 \hat{\lambda}_0 = g_3 \left( \frac{1}{2} \left( \xi^i \frac{\partial}{\partial \eta^j} - \eta^i \frac{\partial}{\partial \xi^j} \right) + ig_3, \right. \] (8.4)
where, however, we now have to sum over \( i \). The different coefficients are due to the different definitions of the covariant derivative, cf (7.7) and also remark 5.11—but note that we used the standard definitions.

Finally, when differentiating the Dirac terms with respect to \( -i \frac{\partial}{\partial \vartheta} \), we obtain
\[ g_3 \hat{\lambda}_0 = ig_3 \hat{\Lambda}_0 = ig_3 \left\{ \frac{1}{2} L^a \xi^a + \varepsilon^a \varepsilon^{R \alpha} \right\}, \] (8.5)
where the summation convention is in place for all indices.

Hence the constraint equation is
\[ (\lambda_0 + g_3 \hat{\lambda}_0 + g_3 \hat{\Lambda}_0) \Psi = 0. \] (8.6)

To solve this equation we first determine the eigenspaces of \( \hat{\lambda}_0 \), or equivalently, of \( \hat{\Lambda}_0 \), which is a self-adjoint operator in the 26-dimensional Hilbert space \( \mathcal{F}_2 \) spanned by the electro-weak fermions. It has nine eigenvalues
\[ 0, \frac{1}{2}, \ldots, \frac{7}{2}, 4 \] (8.7)
which are all multiples of \( \frac{1}{2} \). This claim can be proved by arguing as in the proof of lemma 5.3.

Denote by \( \rho_a, 1 \leq a \leq 9 \), these eigenvalues and by
\[ F_{\rho_a} \] (8.8)
the corresponding eigenspaces; then
\[ \mathcal{F}_2 = \bigoplus_{a=1}^{9} F_{\rho_a}. \] (8.9)
Let $F_{\rho a}$ be arbitrary. We shall use the operator $\tilde{\lambda}_0$ to define a matching function space.

**Theorem 8.1.** For any $r \in \mathbb{Z}$ there exists a largest infinite-dimensional vector space

$$E \subset C^\infty_c(\mathbb{R}^4, \mathbb{C})$$  \hspace{1cm} (8.10)

such that all $u \in E$ satisfy

$$\tilde{\lambda}_0 u = -i^{\frac{r}{2}}u,$$  \hspace{1cm} (8.11)

and such that $E$ will be invariant with respect to the operators $\Delta_{\mathbb{R}^4}$ and

$$u \rightarrow Vu,$$  \hspace{1cm} (8.12)

where the potential $V$ is of the form

$$V = V_0(|z|^2).$$  \hspace{1cm} (8.13)

The claims in remark 5.12 are also valid.

**Proof.** The proof is similar to the proof of theorem 5.9 resp. theorem 5.10. First, let $\rho \in C^\infty_c(\mathbb{R})$; then the functions

$$\varphi = \rho(|\xi|^2),$$  \hspace{1cm} (8.14)

where $\xi^i = \hat{\xi}^i + i\eta^i$, $1 \leq i \leq 2$, satisfy

$$\tilde{\lambda}_0 \varphi = 0.$$  \hspace{1cm} (8.15)

Second, let

$$u_k = \xi^k - i\eta^k \wedge \hat{u}_k = \xi^k + i\eta^k,$$  \hspace{1cm} (8.16)

$1 \leq k \leq 2$ fixed; then

$$\tilde{\lambda}_0 u_k = -i^{\frac{1}{2}}u_k + i\eta^k \wedge \tilde{\lambda}_0 \hat{u}_k = i^{\frac{1}{2}}\hat{u}_k + i\eta^k.$$  \hspace{1cm} (8.17)

For $r \in \mathbb{N}$ define

$$u_a = u_a^\prime \rho(|\xi|^2) \wedge \hat{u} = \hat{u}_a^\prime \rho(|\xi|^2)$$  \hspace{1cm} (8.18)

where $\rho \in C^\infty_c(\mathbb{R})$ is arbitrary; then

$$\tilde{\lambda}_0 u = -i^{\frac{r}{2}}u + i\eta^k \wedge \lambda_0 \hat{u} = i^{\frac{r}{2}}\hat{u} + i\eta^k.$$  \hspace{1cm} (8.19)

and these functions, $u$ resp. $\hat{u}$, generate an infinite-dimensional subspace.

The invariance properties of the subspace can be proved as in the case of theorem 5.9, and the arguments at the end of the proof of that theorem yield the existence of a largest subspace with these properties. \[\square\]

Next we have to define a function space $E_0$ such that

$$\lambda_0 v = 0 \quad \forall v \in E_0.$$  \hspace{1cm} (8.20)

This can be achieved with the help of theorem 5.10. Let $E_0 \subset C^\infty_c(\mathbb{R}^2, \mathbb{C})$ be such that

$$\left( \hat{x} \frac{\partial}{\partial \hat{y}} - \hat{y} \frac{\partial}{\partial \hat{x}} \right) v = -2iv \quad \forall v \in E_0;$$  \hspace{1cm} (8.21)

then

$$\lambda_0 v = 0 \quad \forall v \in E_0.$$  \hspace{1cm} (8.22)
9. The eigenvalue problem for the strong interaction

In this section we solve the free eigenvalue problem for the matter Hamiltonian $H_M$ in the $SU(n)$, $n \geq 2$, model. The Hamiltonian can be expressed in the form

$$H_M \Psi = \left( -a^{ab} \Psi_{ab} + V \Psi \right) + \left( -\frac{1}{2} \Delta \Psi + U \Psi \right) + H_{F_{1}} \Psi,$$

(9.1)

The operator $H_1$ depends on the variables $(\varphi_0, z^i) \in \mathbb{R}^{1+2n}$, $H_2$ on the variables $(\Phi_i) \in \mathbb{R}^{2n}$ and $H_{F_1}$ acts on the fermions in a $2^{2^n}$-dimensional subspace of the antisymmetric Fock space.

Symbolizing the differentiation with respect to $\varphi_0$ by a prime and the Laplace operator with respect to $z \in \mathbb{R}^{2n}$ by $\tilde{\Delta}$, then

$$H_1 \Psi = -\frac{1}{24} \Psi_{\varphi_0}^\prime - \frac{1}{12} \tilde{\Delta} \Psi + V(\varphi_0, z) \Psi.$$  

(9.2)

**Definition 9.1.**

(i) To solve the eigenvalue problem for the operator $H_1$, we choose a largest subspace $E_1 \subset C^\infty_c(\mathbb{R}^{1+2n})$ the elements of which satisfy the constraint equations for the constrained operators $l_{k,m}$ and $l_k$ with eigenvalue $r = 0$ and the invariance conditions, and define the Hilbert spaces $H_1 = \bar{E}_1 \| \cdot \|_1$, as the completion of $E_1$ in the $L^2$-norm, abbreviated simply by $\| \cdot \|$, and $\tilde{H}_1$ as the completion of $E_1$ with respect to the norm

$$\langle u, u \rangle_1 = \| u \|^2_1 = \int_{\mathbb{R} \times \mathbb{R}^{2n}} (|Du|^2 + |x|^4 |u|^2).$$

(9.3)

where $x = (x^i) \in \mathbb{R}^{1+2n}$.

(ii) In the case of the operator $H_2$, we first have to choose one of the joint eigenspaces $F_{\sigma_k}$ of the fermionic constraint operators, cf remark 5.8. Let $E_2 = E_2(\sigma_k)$ be the matching largest subspace of $C^\infty_c(\mathbb{R}^{2n}, \mathbb{C})$ such that the constraint equations will be satisfied for

$$u \otimes \eta, \quad \forall (u, \eta) \in (E_2 \times F_{\sigma_k}).$$

(9.4)

Then we define the Hilbert spaces $H_2 = \tilde{H}_2(\sigma_k)$ as the completion of $E_2$ with respect to the $L^2$-norm

$$\langle u, u \rangle_1 = \| u \|^2_1 = \int_{\mathbb{R}^{2n}} |u|^2.$$

(9.5)

and $\tilde{H}_2$ as the completion of $E_2$ with respect to the norm

$$\langle u, u \rangle_1 = \| u \|^2_1 = \int_{\mathbb{R}^{2n}} (|Du|^2 + |x|^p |u|^2).$$

(9.6)

where $x = (x^i) \in \mathbb{R}^{2n}$ and $p$ being the exponent in (3.34).

We then have to solve three eigenvalue problems for the Hamiltonians $H_i$ in $H_i$, $1 \leq i \leq 2$, and for the fermionic Hamiltonian $H_{F_i}$ restricted to $F_{\sigma_i}$. $H_{F_i}$ corresponds to a quadratic form; i.e. there holds

$$a(\xi, \eta) = \langle H_{F_i} \xi, \eta \rangle \quad \forall \xi, \eta \in F_{1}.$$  

(9.7)

where $a$ is a Hermitian bilinear form. In general the spaces $F_{\sigma_i}$ will not be invariant with respect to $H_{F_i}$—note, however, that the 16 mutually orthogonal unit vectors given in
Lemma 5.7 are all eigenvectors of $H_{F_1}$. We therefore define a new fermionic Hamiltonian operator $H_f = H_f(\sigma_k)$ as the unique self-adjoint operator $H_f \in L(F_{\sigma_k}, F_{\sigma_k})$ satisfying
\[
a(\xi, \eta) = \langle H_f \xi, \eta \rangle \quad \forall \xi, \eta \in F_{\sigma_k}.
\]
Its eigenvectors will then complement the eigenvectors of the bosonic Hamiltonians.

When solving the bosonic problems, it suffices to look at just one operator, and we choose $H_2$ because the corresponding potential $U$ is more general and the proof slightly more elaborate.

**Theorem 9.2.** The linear operator $H_2$ with
\[
D(H_2) = E_2 \subset \mathcal{H}_2
\]
is symmetric and semi-bounded from below. Let $\hat{H}_2$ be its self-adjoint Friedrichs extension; then there exist countably many eigenvectors
\[
u_i \in \hat{\mathcal{H}}_2 \hookrightarrow \mathcal{H}_2
\]
with eigenvalues $\lambda_i$ of finite multiplicities of $\hat{H}$,
\[
\hat{H}_2 \nu_i = \lambda_i \nu_i,
\]
satisfying
\[
\langle \nu_i, \nu_j \rangle = 0 \quad \forall i \neq j,
\]
\[
\lambda_i \leq \lambda_{i+1} \land \lim_{i \to \infty} \lambda_i = \infty.
\]
The $(\nu_i)$ are complete in $\hat{\mathcal{H}}_2$ as well as in $\mathcal{H}_2$.

**Proof.** (i) We shall derive the existence of eigenfunctions from a general variational problem. The symmetric operator $H_2$ defines a sesquilinear form $a$:
\[
a(u, v) = \langle H_2 u, v \rangle = \int_{\mathbb{R}^d} \left\{ \frac{1}{2} D^2 u \bar{v} + \bar{u} D^2 v \right\} \quad \forall u, v \in D(H_2),
\]
where we used that
\[
H_2 u = -\frac{1}{2} \Delta u + U u \quad \forall u \in D(H_2),
\]
and integrated by parts. In view of the estimates (3.34) the quadratic form
\[
a(u, u) + c_2 \|u\|^2
\]
is equivalent to
\[
\langle u, u \rangle_{1,1}.
\]
Furthermore, the norm $\|\cdot\|$ is compact relative to $\|\cdot\|_1$; i.e. if $u_i \rightharpoonup u$ in $\hat{\mathcal{H}}_2$,
\[
\text{then } u_i \to u \text{ in } \mathcal{H}_2,
\]
where we used the trivial embedding
\[
\hat{\mathcal{H}}_2 \hookrightarrow \mathcal{H}_2;
\]
the property described in (9.19), (9.20) can be rephrased that this embedding is compact.

The compactness proof is similar to the proof of [10, lemma 6.8], where a one-dimensional analogue has been considered, but the arguments in the higher dimensional case are the same.
A general variational argument which goes back to Courant–Hilbert, see e.g. [8], then yields the existence of a mutually orthogonal sequence \((u_i)\) of eigenvectors solving the variational relation

\[ a(u_i, v) = \lambda_i \langle u_i, v \rangle \quad \forall \ v \in \tilde{\mathcal{H}}_2, \tag{9.22} \]

such that relations (9.13), (9.14) and the completeness claims in \(\tilde{\mathcal{H}}_2\) as well as \(\mathcal{H}_2\) are valid.

(ii) To prove (9.12) we consider the closure \(\tilde{\mathcal{H}}_2\) of \(\mathcal{H}_2\). Let \(u \in D(\tilde{\mathcal{H}}_2)\); then there exists a sequence \(u_k \in D(\mathcal{H}_2)\) such that

\[ u_k \to u \quad \text{in} \quad \mathcal{H}_2, \tag{9.23} \]

and

\[ \mathcal{H}_2 u_k \to \tilde{\mathcal{H}}_2 u \quad \text{in} \quad \mathcal{H}_2. \tag{9.24} \]

Define \(f_k\) formerly by

\[ f_k = \mathcal{H}_2 u_k. \tag{9.25} \]

Multiplying the equation

\[ \mathcal{H}_2(u_k - u_l) = f_k - f_l \tag{9.26} \]

by \((\bar{u}_k - \bar{u}_l)\) and integrating by parts we conclude

\[ a(u_k - u_l, u_k - u_l) \leq \| f_k - f_l \| \| u_k - u_l \|; \tag{9.27} \]

hence, \((u_k)\) is also a Cauchy sequence in \(\tilde{\mathcal{H}}_2\), and we conclude further

\[ D(\tilde{\mathcal{H}}) \subset \tilde{\mathcal{H}}_2. \tag{9.28} \]

The Friedrichs extension \(\tilde{\mathcal{H}}_2\) of \(\mathcal{H}_2\) is then defined by

\[ \tilde{\mathcal{H}}_2 = \mathcal{H}_2^* \mid_{D(\mathcal{H}_2^*)}; \tag{9.29} \]

where \(\mathcal{H}_2^*\) is the adjoint of \(\mathcal{H}_2\).

Now, let \(u_i\) be an arbitrary solution of (9.22); then we deduce immediately

\[ u_i \in D(\mathcal{H}_2^*) \wedge \mathcal{H}_2^* u_i = \lambda_i u_i, \tag{9.30} \]

proving (9.12). \(\square\)

A finite number of the eigenvalues \(\lambda_i\) of the variational solutions can be negative, since the potential \(U\) is not supposed to be non-negative, but only subject to the estimates in (3.34).

The positivity of the smallest eigenvalue \(\lambda_0\) can be guaranteed under the following assumptions.

**Theorem 9.3.** Let \(c_1, c_2\) be the constants in (3.34) and let \(c_1\) be fixed; then there exists a positive constant \(c_0\) such that the smallest eigenvalue \(\lambda_0\) of the variational problems (9.22) is strictly positive provided

\[ c_2 < c_0. \tag{9.31} \]

Moreover, for fixed \(c_2\), let

\[ \lambda_0 = \lambda_0(c_1) \tag{9.32} \]

be the smallest eigenvalue; then

\[ \lim_{c_1 \to \infty} \lambda_0(c_1) = \infty. \tag{9.33} \]
Proof. (i) Let us first prove the positivity of \( \lambda_0 \), if (9.31) is satisfied. The eigenfunction of the smallest eigenvalue \( \lambda_0 \) is a solution of the variational problem
\[
J(v) = \int_{\mathbb{R}^n} \left( \frac{1}{2} |Dv|^2 + U|v|^2 \right) \to \min \quad \forall \ v \in K,
\]
where
\[
K = \{ v \in \tilde{H}_2 : \|v\| = 1 \}.
\]
In view of (3.34) \( J \) can be estimated from below by
\[
\int_{\mathbb{R}^n} \left( \frac{1}{2} |Dv|^2 + c_1|x|^{2p}|v|^2 - c_2|v|^2 \right).
\]
Denote by \( \tilde{J} \) the functional
\[
\tilde{J}(v) = \int_{\mathbb{R}^n} \left( \frac{1}{2} |Dv|^2 + c_1|x|^{2p}|v|^2 \right);
\]
then the variational problem
\[
\tilde{J}(v) \to \min \quad \forall \ v \in K
\]
has a solution \( \tilde{u}_0 \) with eigenvalue \( \tilde{\lambda}_0 > 0 \); i.e. there holds
\[
0 < \tilde{\lambda}_0 = \tilde{J}(\tilde{u}_0) \leq \tilde{J}(v) \quad \forall \ v \in K.
\]
Thus, setting
\[
c_0 = \tilde{\lambda}_0
\]
will prove the first claim.
(ii) To prove (9.33), we argue by contradiction. Let \( c_{1,k} \) be a sequence converging to infinity and \( u_k \) a corresponding sequence of first eigenfunctions such that
\[
\lambda_{0,k} \leq \text{const} \quad \forall \ k.
\]
Hence, we have
\[
J(u_k) = \lambda_{0,k} = \lambda_{0,k} \|u_k\|^2.
\]
Since \( c_2 \) is fixed, we deduce from (9.36)
\[
\int_{\mathbb{R}^n} \left( \frac{1}{2} |Du_k|^2 + c_{1,k}|x|^{2p}|u_k|^2 \right) \leq \lambda_{0,k} + c_2 \leq c.
\]
The sequence \( (u_k) \) is therefore bounded in \( \tilde{H}_2 \) and
\[
\lim_{k \to \infty} \int_{\mathbb{R}^n} |x|^{2p}|u_k|^2 = 0,
\]
and we conclude, since the embedding
\[
\tilde{H}_2 \hookrightarrow H_2
\]
is compact, that a subsequence, not relabelled, converges weakly in \( \tilde{H}_2 \) to a function \( u \) such that
\[
u_k \to u \quad \text{in} \ \tilde{H}_2;
\]
hence, \( \|u\| = 1 \) contradicting
\[
\int_{\mathbb{R}^n} |x|^{2p}|u|^2 \leq \lim \int_{\mathbb{R}^n} |x|^{2p}|u_k|^2 = 0.
\]
\( \square \)
For the Hamiltonian $H_1$ similar results are valid. The potential $V$ then satisfies
\[ c_1 |x|^4 \leq V, \quad c_1 > 0, \] (9.48)
if $x = (x^i) \in \mathbb{R}^{1+2n}$. Hence, the smallest eigenvalue $\lambda_0$ is always positive, but we cannot manipulate its size, since we cannot adjust $V$.

Combining the results for the Hamiltonians $H_1, H_2$ and $H_{F_1}$ we have proved

**Theorem 9.4.** For each $F_{\alpha_k} \subset F_1$, $1 \leq k \leq 9$, there exist infinite-dimensional Hilbert spaces $\mathcal{H}_1$ and $\mathcal{H}_2$ and corresponding self-adjoint operators $\hat{H}_1, \hat{H}_2$ and $H_f$ in $F_{\alpha_k}$, such that the functions in
\[ \mathcal{H}_1 \otimes \mathcal{H}_2 \otimes F_{\alpha_k} \] (9.49)
satisfy the constraint equations, and complete sequences of eigenfunctions
\[ u_i \in \mathcal{H}_1 \wedge v_j \in \mathcal{H}_2 \] (9.50)
for $\hat{H}_1$ resp. $\hat{H}_2$ and finitely many eigenvectors for $H_f$
\[ \eta_l \in F_{\alpha_k}. \] (9.51)

The products
\[ \Psi_{ijl} = u_i \otimes v_j \otimes \eta_l \] (9.52)
are then eigenfunctions of
\[ \hat{H}_1 + \hat{H}_2 + H_f. \] (9.53)

Relabelling the eigenvalues and eigenfunctions we get a sequence of eigenvalues $\lambda_i$ and corresponding eigenfunctions $\Psi_i$ such that
\[ 0 < \lambda_i \leq \lambda_{i+1} \wedge \lim \lambda_i = \infty, \] (9.54)
\[ \hat{H}_2 \Psi_i = \lambda_i \Psi_i, \] (9.55)
where, by abusing the notation, we define
\[ \hat{H}_2 = \hat{H}_1 + \hat{H}_2 + H_f, \] (9.56)
and
\[ D(\hat{H}_2) = \langle \Psi_i \rangle_{i \in \mathbb{N}}. \] (9.57)
$\hat{H}_2$ is then essentially self-adjoint in
\[ \mathcal{H}_2 = \mathcal{H}_1 \otimes \mathcal{H}_2 \otimes F_{\alpha_k}. \] (9.58)

**10. The eigenvalue problem for the electro-weak interaction**

The matter Hamiltonian of the electro-weak interaction is the sum of two Hamiltonians which are strongly coupled and cannot be treated separately:
\[ H_{M_{\text{el}}} = H_3 + H_{F_2}. \] (10.1)
The bosonic variables are $(\tilde{\phi}, \hat{\phi}_0, \hat{z}, \phi')$, where $\tilde{\phi}, \hat{\phi}_0$ are real variables, $\hat{z}$ is complex and $(\phi')$ is a complex doublet, the Higgs field. Only $\hat{z}$ and $\phi'$ are related to the constraint equations.

Let us denote the coordinates according to
\[ (\tilde{\phi}, \phi_0, \hat{z}, \phi') \rightarrow (x, y, \hat{x} + i \hat{y}, \xi + i \eta') \] (10.2)
and the Laplacians in $\mathbb{R}^2$ resp. $\mathbb{R}^4$ by $\hat{\Delta}$ resp. $\hat{\Delta}$. 

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With these notations there holds
\[ H_3 \Psi = \frac{1}{12} \frac{\partial^2 \Psi}{\partial x^2} - \frac{1}{24} \frac{\partial^2 \Psi}{\partial y^2} - \frac{1}{12} \Delta \Psi - \frac{1}{2} \Delta \Psi + \hat{V} + \hat{U} \]
\[ + 3x^4 + 3\mu x^2 + \frac{3}{2} g_2^2 x^2 (|\xi|^2 + |\eta|^2) + \frac{3}{2} g_2 x \tilde{L}_\alpha^a L_\alpha^i \]
\[ + h_\gamma (\xi^i \bar{e}_R^a L_\alpha^a + \bar{L}_\alpha^a e_R^a) + \eta_i (\gamma^a \bar{L}_\alpha^a + \bar{i}L_\alpha^a e_R^a), \]  
(10.3)
where \( 1 \leq \alpha \leq 2, 1 \leq i \leq 2. \)

The potential \( \hat{V} \) is defined by
\[ \hat{V} = |y|^4 + 8y^2 (\hat{x}^2 + \hat{y}^2) + (\hat{x}^2 + \hat{y}^2)^2, \]  
(10.4)
and \( \hat{U} \) by
\[ \hat{U} = b_0 (|\xi|^2 + |\eta|^2)^2 - m_1 (|\xi|^2 + |\eta|^2), \]  
(10.5)
where \( b_0 > 0 \) and \( m_1 \) can be real or imaginary.

Let \( \bar{V} \) be the potential
\[ \bar{V} = 3x^4 + 3\mu x^2 + \frac{3}{2} g_2^2 x^2 (|\xi|^2 + |\eta|^2); \]  
(10.6)
then we see that the sum of all three potentials has the same structure as the potentials in the case of the strong interaction, namely
\[ -c_1 + c_1 |x|^4 \leq \bar{V} + \hat{V} + \hat{U} \leq c'_1 |x|^4 + c'_2, \]  
(10.7)
where \( x \in \mathbb{R}^8 \)—but this usage is restricted to this particular estimate.

We also see that the fermionic operators have coefficients depending on \((x, \xi^k, \eta^k)\) and therefore the eigenvalue problem cannot be separated in bosonic and fermionic parts but has to treated in a fermion-valued function space. The eigenfunctions will be non-trivial fermionic fields
\[ \Psi : \mathbb{R}^8 \rightarrow \mathcal{F}_2, \]  
(10.8)
where \( \mathcal{F}_2 \) is the subspace of the antisymmetric Fock space spanned by the fermions.

\( H_3 \) is obviously formerly self-adjoint and the eigenvalues of the fermionic operators—disregarding their coefficients as well as \( g_2 \) and \( h_\gamma \)—are absolutely bounded by a numerical constant \( \alpha_0. \)

Thus, using the symbol \( u \) instead of \( \Psi, \) if
\[ u, v \in C_c^\infty (\mathbb{R}^8, \mathcal{F}_2) \]  
(10.9)
then
\[ \langle H_3 u, v \rangle = \langle u, H_3 v \rangle \]  
(10.10)
and
\[ \langle H_3 u, u \rangle = \int_{\mathbb{R}^8} \left\{ a^{ij} (D_i u, D_j u) + (\bar{V} + \hat{V} + \hat{U}) \|u\|^2 \right. \]
\[ + \frac{3}{2} g_2 x a_0 (u, u) + h_\gamma (\xi^k a_k (u, u) + \eta^k b_k (u, u)) \left\}, \]  
(10.11)
where
\[ -a^{ij} D_i D_j u \]  
(10.12)
represents the elliptic main differential part of \( H_3, \) and \( a_0, a_k, b_k, 1 \leq k \leq 2, \) are the sesquilinear fermionic forms, e.g.
\[ a_0 = \frac{1}{2} \tilde{L}_\alpha^a L_\alpha^i, \]  
(10.13)
and the scalar product under the integral sign is the scalar product in $\mathcal{F}_2$ with corresponding norm $\|\cdot\|$.

Let $\chi \in \mathcal{F}_2$ be normalized, $\|\chi\| = 1$; then

$$\max(\|a_0(\chi, \chi)\|, \|a_k(\chi, \chi)\|, \|b_k(\chi, \chi)\|) \leq a_0 \quad \forall 1 \leq k \leq 2,$$

(10.14)

and we deduce that for any $\delta > 0$

$$\langle H_3 u, u \rangle \geq \int_{\mathbb{R}^8} \{ a_{ij}(Du, D_j u) + (\bar{V} + \bar{\tilde{V}} + \bar{U})\|u\|^2$$

$$- c (\frac{g_2}{2} |x|^2 + h_2^2 (|\xi|^2 + |\eta|^2)) \alpha_0 \delta^{-1} \|u\|^2 - \delta \|u\|^2 \},$$

(10.15)

where $c$ is a numerical constant.

Note that $u$ has values in $\mathcal{F}_2$; i.e. if we fix an orthonormal basis in $\mathcal{F}_2$,

$$u = (u^A),$$

(10.16)

then

$$a_{ij}(D_i u, D_j u) = a_{ij} D_i u^A D_j u_A$$

(10.17)

and

$$c_1 \|Du\|^2 \leq a_{ij}(D_i u, D_j u) \leq c_2 \|Du\|^2,$$

(10.18)

where $c_1, c_2$ are the positive numerical constants, and the norm is the norm in $\mathcal{F}_2$.

To solve the eigenvalue problem we first have to define the Hilbert space. First we fix an eigenspace $\mathcal{F}_\rho_a$, $1 \leq a \leq 9$, of $\hat{\lambda}_0$ in $\mathcal{F}_2$, cf (8.9), and let $E_0 \subset C^\infty_c (\mathbb{R}^4, \mathbb{C})$ resp. $E \subset C^\infty_c (\mathbb{R}^4, \mathbb{C})$ be matching subspaces, cf theorem 8.1 and the remarks at the end of section 8. Then we define

$$E = E(\rho_a) = E_0 \otimes E \otimes \mathcal{F}_\rho_a$$

(10.19)

and consider $E$ as a subspace of $C^\infty_c (\mathbb{R}^8, \mathcal{F}_\rho_a)$:

$$E \subset C^\infty_c (\mathbb{R}^8, \mathcal{F}_\rho_a),$$

(10.20)

where its elements are functions

$$u = u(x) = (u^A)$$

(10.21)

with the pointwise norm

$$\|u\|^2 = u^A \bar{u}^A.$$

(10.22)

**Definition 10.1.** Let $\mathcal{H}_3$ be the completion of $E$ with respect to the $L^2$-norm, where we define for $u \in E$

$$\|u\|^2 = \int_{\mathbb{R}^8} \|u\|^2;$$

(10.23)

the norm inside the integral is the norm in $\mathcal{F}_2$.

The Hilbert space $\tilde{\mathcal{H}}_3$ is defined as the completion of $E$ with respect to the norm

$$\|u\|^2_1 = \int_{\mathbb{R}^8} \{ \|Du\|^2 + |x|^4 \|u\|^2 \}.$$

(10.24)

Though $E$ is invariant with respect to the potentials and the respective Laplace operators it is not invariant with respect to $H_3$ because of the fermionic operators which also depend on spatial variables. To define a meaningful symmetric operator satisfying the constraints,
we consider the quadratic form associated with $H_3$ which is defined in (10.11). Denote this quadratic form by $a_3$,
\[ a_3(u, v) = \langle H_3 u, v \rangle \quad \forall u, v \in E. \tag{10.25} \]
In view of the estimate in (10.15), $a_3$ is semi-bounded from below in $\tilde{H}_3$, or more precisely, we have
\[ a_3(u, u) \geq c_1 \| u \|^2_1 - c_2 \| u \|^2 \quad \forall u \in E; \tag{10.26} \]
for a proof simply choose the parameter $\delta$ in (10.15) large enough.

On the other hand, $a_3$ can be estimated from above by
\[ a_3(u, u) \leq c'_1 \| u \|^2_1 + c'_2 \| u \|^2 \quad \forall u \in E, \tag{10.27} \]
where the second inequality is valid because the embedding
\[ \tilde{H}_3 \hookrightarrow H_3 \] (10.28)
is compact; the constant $c'_1$ in the second inequality is of course different from the corresponding constant in the first inequality.

Thus, $a_3$ has a natural extension to $\tilde{H}_3$ and we can apply the general variational principle to find a complete set of eigenfunctions.

**Theorem 10.2.** There exists a sequence of normalized eigenfunctions $u_i$ with real eigenvalues $\lambda_i$ of finite multiplicities such that
\[ a_3(u_i, v) = \lambda_i \langle u_i, v \rangle \quad \forall v \in \tilde{H}_3, \tag{10.29} \]
\[ \lambda_i \leq \lambda_{i+1} \land \lim \lambda_i = \infty, \tag{10.30} \]
and
\[ a_3(u_i, u_j) = \langle u_i, u_j \rangle = 0 \quad \forall i \neq j. \tag{10.31} \]

Define the linear operator $T_3$ by
\[ D(T_3) = \langle (u_i)_{i \in \mathbb{N}} \rangle \land T_3 u_i = \lambda_i u_i \quad \forall i \in \mathbb{N}; \tag{10.32} \]
then $T_3$ is densely defined in $\tilde{H}_3$, symmetric, essentially self-adjoint and there holds
\[ a_3(u, v) = \langle T_3 u, v \rangle \quad \forall u, v \in D(T_3). \tag{10.33} \]

**Proof.** We only have to prove the claims about the operator $T_3$. $T_3$ is certainly densely defined and satisfies (10.33), since this relation is valid for $u = u_i$

Hence $T_3$ is symmetric and it remains to prove the essential self-adjointness. Thus it suffices to prove
\[ R(T_3 \pm i) = \tilde{H}_3. \tag{10.34} \]
But these relations are obviously valid, since
\[ u_i \in R(T_3 \pm i) \quad \forall i. \tag{10.35} \]

The closure of $T_3$ is then the self-adjoint operator we are looking for:
\[ \tilde{H}_3 = \tilde{H}_3(\rho_0) = \tilde{T}_3. \tag{10.36} \]

As in the case of the strong interaction, a finite number of eigenvalues could be negative. This can be excluded by adjusting the free parameters $\tilde{\mu}$ and $b_0$ in the potentials $\tilde{V}$ and $\tilde{U}$ appropriately.
Using the notations in (10.2), (10.3) and the definitions of the potentials \(\bar{V}, \hat{V}, \hat{U}\) in (10.6), (10.4), (10.5) we infer
\[
\bar{V} + \hat{V} + \hat{U} \geq 3\bar{\mu}|x|^2 + b_0(|\xi|^2 + |\eta|^2)^2 + 3|x|^4 + |y|^4 + (\hat{x}^2 + \hat{y}^2)^2 - m_1^2(|\xi|^2 + |\eta|^2),
\]
and we conclude further, in view of (10.15),
\[
a_3(u, u) \geq \int_{\mathbb{R}^4} \left\{ c_1 \|Du\|^2 + \left( b_0 - \frac{c^2}{2} \right) \hat{x}^2 + \hat{y}^2 \right\}
+ 3|x|^4 + |y|^4 + (\hat{x}^2 + \hat{y}^2)^2 - 2\delta \|u\|^2.
\]
provided
\[
3\bar{\mu} \geq c\gamma_2^2 \alpha_0^2 \delta^{-1}.
\]
Hence, we conclude, as in the proof of theorem 9.3:

**Theorem 10.3.** There exists a constant \(\delta = \delta(c_1) > 0\) such that the eigenvalues \(\lambda_i\) are strictly positive provided
\[
b_0 \geq \frac{c^2}{2} \hat{x}^2 + \frac{|m_1|^2}{2} \delta^{-1} + 1\]
and \(\bar{\mu}\) satisfies (10.39).

We have thus solved the eigenvalue problem for each subspace \(F_{\rho_\sigma} \subset \mathcal{F}_2\) in a corresponding Hilbert space
\[
\mathcal{H}_3(\rho_\sigma).
\]
These Hilbert spaces are mutually orthogonal subspaces of
\[
L^2(\mathbb{R}^8) \otimes \mathcal{F}_2 \cong L^2(\mathbb{R}^8, \mathcal{F}_2).
\]
The self-adjoint operators \(\hat{H}_{\rho_\sigma}\) then define a unique self-adjoint operator \(\hat{H}_3\) in
\[
\bigoplus_{a=1}^9 \mathcal{H}_3(\rho_\sigma)
\]
such that
\[
\hat{H}_{3[S_{\rho_\sigma}]} = \hat{H}_3(\rho_\sigma) \quad \forall 1 \leq a \leq 9.
\]

11. The spectral resolution

We shall now prove the spectral resolution of the Wheeler–DeWitt equation for the full Hamiltonian when gravity is combined with the strong and electro-weak interactions. Our proof will even be valid when a finite number of matter fields are involved. However, except for the actual proof, we shall only consider the two interactions we are dealing with to simplify the presentation.

For arbitrary but fixed \(\sigma_k, \rho_a, 1 \leq a, k \leq 9\), let \(\mathcal{H}_2(\sigma_k), \mathcal{H}_3(\rho_a)\) be the corresponding Hilbert spaces and \(\hat{H}_2\) resp. \(\hat{H}_3\) the (essentially) self-adjoint operators solving the eigenvalue problems
\[
\hat{H}_2 u_i = \lambda_i u_i \quad u_i \in \mathcal{H}_2,
\]
resp.
\[
\hat{H}_3 v_j = \mu_j v_j \quad v_j \in \mathcal{H}_3,
\]
cf theorem 9.4 resp. theorem 10.2.
The functions
\[ \phi_{ij} = u_i \otimes v_j \in \mathcal{H}_2 \otimes \mathcal{H}_3 \]  
are then eigenfunctions of the operator
\[ \hat{H}_i = \hat{H}_2 + \hat{H}_3, \]  
\[ \hat{H}_i \phi_{ij} = (\lambda_i + \mu_j) \phi_{ij}, \]
where
\[ D(\hat{H}_i) = \{(\phi_{ij})_{i,j} \in \mathbb{N} \times \mathbb{N}\}. \]

We require that
\[ \lambda_i + \mu_j > 0 \quad \forall (i,j). \]

In view of the results in theorem 9.3 and theorem 10.3 this can always be achieved by choosing the parameters in the potentials appropriately.

After relabelling the countably many eigenvalues and eigenfunctions we may assume that 
\( (\phi_i, \mu_i) \) are the solutions of the eigenvalue problem for \( \hat{H}_1 \) satisfying
\[ \hat{H}_i \phi_i = \mu_i \phi_i \]
such that the \( (\phi_i) \) are complete in \( \mathcal{H}_1 = \mathcal{H}_2 \otimes \mathcal{H}_3 \) and the eigenvalues \( \mu_i \) have finite multiplicities such that
\[ 0 < \mu_i \leq \mu_{i+1} \land \lim \mu_i = \infty. \]

We also note that the elements \( \phi \in \mathcal{H}_1 \) are viewed as maps
\[ \phi : \mathbb{R}^{4n+9} \to F_{\rho_0} \otimes F_{\rho_2} \subset F_1 \otimes F_2, \]
i.e.
\[ \mathcal{H}_1 \subset L^2(\mathbb{R}^{4n+9}, F_1 \otimes F_2) \]
We are therefore in a similar situation as in [11], where we considered a related problem.

The Wheeler–DeWitt equation can now be written in the form
\[ H_0 \Psi - \hat{H}_1 \Psi = 0, \]
where \( \Psi \) has to satisfy the constraints. The constraints will be satisfied, if we split \( \Psi \) in the form
\[ \Psi = u \otimes \phi, \]
where \( \phi \in \mathcal{H}_1 \) and \( u \) is a complex-valued function
\[ u = u(f) \equiv u(t) \]
depending on the real variable \( f \) which we shall also denote by \( t \).

The operator \( H_0 \) is the differential operator
\[ H_0 u = -\frac{\alpha M}{24} e^{-2(2n+5)t} (e^{(2n+3)t} u')' - 2\alpha M A e^{4t} u \]
cf (7.16), where a dot or prime indicates differentiation with respect to \( t \).

The exponents \((2n + 3)\) resp. \((2n + 5)\) depend on the number of the bosonic dynamical variables. To solve the Wheeler–DeWitt equation for an arbitrary number of matter fields with \( m \) dynamical bosonic variables, we consider the operator
\[ H_0 u = -\frac{\alpha M}{24} e^{-\frac{(2n+3)}{2} \cdot t} \left( e^{\frac{(2n+3)}{2} t} u' \right)' - 2\alpha M A e^{4t} u. \]
In our present situation there holds
\[ m = 4n + 9. \]  \hfill (11.17)

Let \( \tilde{H}_0 \) be defined by
\[ \tilde{H}_0 u = -\frac{\alpha M}{24} e^{-\frac{m+3}{2}t} \left( e^{-\frac{m+3}{2}t} u' \right)' + 2\alpha e^{4t} u. \]  \hfill (11.18)

Then, we first solve the eigenvalue problems
\[ \tilde{H}_0 u = \lambda u \]  \hfill (11.19)
in an appropriate function space.

**Definition 11.1.** For \( p = \frac{m-1}{2} \) define \( H_0 \) as the completion of \( C_\infty^c (\mathbb{R}, \mathbb{C}) \) with respect to the norm
\[ \| u \|^2 = \int_\mathbb{R} |u|^2 e^{(p+2)t} \]  \hfill (11.20)
and \( \tilde{H}_0 \) as the completion of \( C_\infty^c (\mathbb{R}, \mathbb{C}) \) with respect to the norm
\[ \| u \|^2_1 = \int_\mathbb{R} \left( |u|^2 e^{pt} + |u|^2 e^{(p+6)t} \right). \]  \hfill (11.21)

**Lemma 11.2.** The norm \( \| \cdot \| \) is compact relative to \( \| \cdot \|_1 \).

**Proof.** Let \( u_k \subset \tilde{H}_0 \) be a sequence converging weakly to zero; then we have to prove
\[ \lim \| u_k \| = 0. \]  \hfill (11.22)
Let \( I = (a, b) \) be any bounded interval and \( \chi = \chi_I \) be its characteristic function; then
\[ \lim \| u_k \chi_I \| = 0, \]  \hfill (11.23)
in view of the Sobolev embedding theorem stating that the embedding
\[ H^{1,2}(I) \hookrightarrow L^2(I) \]  \hfill (11.24)
is compact.

Thus, we only have to prove
\[ \limsup \int_b^\infty |u_k|^2 e^{(p+2)t} \leq \epsilon(b), \]  \hfill (11.25)
where
\[ \lim_{b \to \infty} \epsilon(b) = 0, \]  \hfill (11.26)
and a similar estimate in \(( -\infty, b), b \ll -1, \)
\[ \limsup \int_{-\infty}^b |u_k|^2 e^{(p+2)t} \leq \epsilon(b). \]  \hfill (11.27)

Let us first prove (11.25), which is almost trivial. From
\[ \| u_k \|_1 \leq c \quad \forall k \]  \hfill (11.28)
we deduce
\[ \int_b^\infty |u_k|^2 e^{(p+2)t} \leq e^{-4b} \int_b^\infty |u_k|^2 e^{(p+6)t} \leq c e^{-4b} = \epsilon(b), \]  \hfill (11.29)
which implies (11.26).
The proof of (11.27) is a bit more delicate. First, we make a change in variables setting
\[ \tau = -t \] (11.30)
such that the crucial estimate for \( u_k = u_k(\tau) \) is
\[ \lim \sup \int_0^\infty |u_k|^2 e^{-(p+2)\tau} \leq \epsilon(b). \] (11.31)
Replacing \( u_k \) by \( u_k \eta \), (11.32)
where \( \eta \) is a cut-off function, we may assume without loss of generality that
\[ \text{supp} u_k \subset (\tau_1, \infty), \quad \tau_1 > 3. \] (11.33)
We then only use the estimate
\[ \int_0^\infty |\dot{u}_k|^2 e^{-p\tau} \leq c \quad \forall k \] (11.34)
and the Hardy–Littlewood inequality
\[ \int_0^\infty |u|^2 \tau^{-\sigma} \leq \left( \frac{2}{|\sigma - 1|} \right)^2 \int_0^\infty |u|^2 \tau^{(-\sigma+2)}, \] (11.35)
which is valid for all \( u \in C_\infty^c(\mathbb{R}_+) \) and all \( 1 \neq \sigma \in \mathbb{R} \), cf [12, theorem 3.30].
We distinguish two cases.

**Case 1:** \( p = 0 \).

Then, we may choose in (11.35) \( \sigma = 2 \) and \( u = u_k \) to deduce
\[ \int_0^\infty |u_k|^2 e^{-2\tau} \leq 4 \int_0^\infty |\dot{u}_k|^2 \leq 4c, \] (11.36)
and we conclude further
\[ \int_0^\infty |u_k|^2 e^{-2\tau} \leq b^2 e^{-2b} \int_0^\infty |u_k|^2 \tau^{-2}, \] (11.37)
if \( b > 1 \), hence the result.

**Case 2:** \( p \neq 0 \).

If \( p \neq 0 \), we employ another variable transformation
\[ r = e^\tau, \] (11.38)
such that
\[ \frac{d}{dr} u \equiv \dot{u} = \frac{d}{dr} u e^\tau \equiv \dot{u} e^\tau, \] (11.39)
and we infer
\[ \int_0^\infty |u_k|^2 r^{1-p} = \int_0^\infty |\dot{u}_k|^2 e^{-p\tau} \leq c, \] (11.40)
in view of (11.33) and (11.34).
Thus, we may apply the Hardy–Littlewood inequality with
\[ \sigma = p + 1 \] (11.41)
to derive
\[ \int_{r_0}^\infty |u_k|^2 r^{-(p+3)} \leq r_0^{-2} \int_{r_0}^\infty |\dot{u}_k|^2 r^{-(p+1)} \leq c r_0^{-2} = \epsilon(r_0), \quad r_0 > 1, \] (11.42)
where we used (11.33), completing the proof of the lemma. \( \square \)
Let \( \langle u, v \rangle \) be the scalar product
\[
\langle u, v \rangle = \int \overline{u} \nu e^{pt}
\]
in \( \mathcal{H}_0 \) and
\[
a(u, v) = \langle \tilde{H}_0 u, v \rangle = \int \{ \frac{\alpha_M}{24} \overline{u} \nu + 2 \alpha_M^{-1} \overline{u} \nu e^{(p+6)t} \} \forall u, v \in \tilde{\mathcal{H}}_0;
\]
then, by applying the general variational eigenvalue principle, we obtain

**Theorem 11.3.** There exists a sequence of normalized eigenfunctions \( \tilde{u}_i \) with strictly positive eigenvalues \( \tilde{\lambda}_i \) with finite multiplicities such that
\[
0 < \tilde{\lambda}_i \leq \tilde{\lambda}_{i+1} \land \lim \tilde{\lambda}_i = \infty,
\]
and
\[
a(\tilde{u}_i, v) = \tilde{\lambda}_i \langle \tilde{u}_i, v \rangle \quad \forall v \in \tilde{\mathcal{H}}_0,
\]
and
\[
a(\tilde{u}_i, \tilde{u}_j) = \langle u_i, u_j \rangle = 0 \quad \forall i \neq j.
\]

Define the linear operator \( \tilde{H} \) by
\[
D(\tilde{H}) = \langle (\tilde{u}_i)_{i \in \mathbb{N}} \rangle \land \tilde{H} \tilde{u}_i = \tilde{\lambda}_i \tilde{u}_i \quad \forall i;
\]
then \( \tilde{H} \) is densely defined in \( \mathcal{H}_0 \), symmetric, essentially self-adjoint and
\[
a(u, v) = \langle \tilde{H} u, v \rangle \quad \forall u, v \in D(\tilde{H}).
\]
Moreover, there holds
\[
\tilde{H}_0 \tilde{u}_i = \tilde{H} \tilde{u}_i = \tilde{\lambda}_i \tilde{u}_i.
\]

**Proof.** We only have to prove (11.50) and (11.51), since the proof of the other statements is identical to the proof of theorem 10.2.

From (11.46) we immediately deduce
\[
\tilde{H}_0 \tilde{u}_i = \tilde{\lambda}_i \tilde{u}_i
\]
in the distributional sense; hence (11.50) is valid, which in turn implies (11.51).

An immediate consequence of the preceding result is

**Theorem 11.4.** Let \( \mu > 0 \); then the pairs \( (\tilde{u}_i, \tilde{\lambda}_i) \) represent a complete set of eigenfunctions with eigenvalues
\[
\lambda_i = \tilde{\lambda}_i \mu^{-1}
\]
for the eigenvalue problems
\[
\tilde{H}_0 u = \lambda \mu u.
\]
The rescaled functions
\[
u_i(t) = \tilde{u}_i \left( t - \frac{1}{2} \log \lambda_i \right)
\]
then satisfy
\[
-\frac{\alpha_M}{24} \left(e^{-(m+1)}(e^{-(m+1)}u_i)\right) + 2 \alpha_M^{-1} \lambda_i^{-3} e^{u_i} = \mu u_i,
\]
or, if we set

$$
\Lambda_i = -\lambda_{ij}^{-3},
$$
(11.57)

$$
-\frac{\alpha_M}{24} e^{-\frac{\alpha_M}{24}} \left( e^{\frac{\alpha_M}{24}} u_i \right)' - 2\alpha_M \Lambda_i e^{\alpha_M} u_i = \mu u_i.
$$
(11.58)

We can now prove the spectral resolution of the Wheeler–DeWitt equation. Let \((\mu, \phi)\) resp. \((\lambda, \tilde{u})\) be a solution of

$$
\hat{H}_1 \phi = \mu \phi
$$
(11.59)

resp.

$$
\tilde{H}_0 \tilde{u} = \lambda \mu \tilde{u},
$$
(11.60)

and set

$$
\Psi = \tilde{u} \otimes \phi;
$$
(11.61)

then

$$
\hat{H}_0 \Psi = \lambda \hat{H}_1 \Psi,
$$
(11.62)

or equivalently, in view of the preceding theorem,

$$
H_0 \Psi - \hat{H}_1 \Psi = 0,
$$
(11.63)

where

$$
\Psi = u \otimes \varphi,
$$
(11.64)

$$
u(t) = \tilde{u} \left(t - \frac{1}{2} \log \lambda \right),
$$
(11.65)

$$
H_0 \Psi = -\frac{\alpha_M}{24} e^{-\frac{\alpha_M}{24}} \left( e^{\frac{\alpha_M}{24}} \psi' \right)' - 2\alpha_M \Lambda e^{\alpha_M} \psi,
$$
(11.66)

and

$$
\Lambda = -\lambda_{ij}^{-3}.
$$
(11.67)

One easily checks that \(\Psi\) belongs to

$$
\tilde{H}_0 \otimes \tilde{H}_1 \subset H_0 \otimes H_1,
$$
(11.68)

cf the corresponding considerations in [11, section 3].

Let \(\tilde{u}_i\) resp. \(\varphi_j\) be the eigenfunctions of \(\tilde{H}_0\) resp. \(\hat{H}_1\); then

$$
\tilde{\Psi}_{ij} = \tilde{u}_i \otimes \varphi_j
$$
(11.69)

form a complete set of eigenfunctions in \(\tilde{H}_0 \otimes H_1\) of the linear operator

$$
H = \tilde{H}_0 \hat{H}_1^{-1} = \hat{H}_1^{-1} \tilde{H}_0,
$$
(11.70)

such that

$$
H \tilde{\Psi}_{ij} = \lambda_{ij} \tilde{\Psi}_{ij} = \lambda_i \mu_j^{-1} \tilde{\Psi}_{ij},
$$
(11.71)

where

$$
D(H) = \{(\tilde{\Psi}_{ij})_{(i,j)\in\mathbb{N}\times\mathbb{N}}\}.
$$
(11.72)

The rescaled functions

$$
\Psi(t, \cdot) = \tilde{\Psi} \left(t - \frac{1}{2} \log \lambda_{ij}, \cdot \right)
$$
(11.73)
are the solutions of the Wheeler–DeWitt equation with the cosmological constant
\[
\Lambda_{ij} = -\lambda_{ij}^{-3}.
\] (11.74)

**Remark 11.5.** \(H\) is essentially self-adjoint in \(\mathcal{H}_0 \otimes \mathcal{H}_4\) and we consider it to be the Hamiltonian associated with the physical system defined by the interaction of gravity with the matter fields. The properly rescaled eigenfunctions \(\Psi_{ij}\) are the solutions of the Wheeler–DeWitt equation. We refer to [11, section 3], where these connections have been explained and proved in greater detail.

The wavefunctions \(\Psi\) are maps from
\[
\Psi : \mathbb{R}^{4n+10} \rightarrow \mathcal{F}_1 \otimes \mathcal{F}_2
\] (11.75)
and in general the eigenstates \(\Psi\) cannot be written as simple products
\[
\Psi = u\eta,
\] (11.76)
such that
\[
\eta \in \mathcal{F}_1 \otimes \mathcal{F}_2 \wedge u(x) \in \mathbb{C} \quad \forall x \in \mathbb{R}^{4n+10}.
\] (11.77)
Thus, in general it makes no sense specifying a fermion \(\eta\) and looking for an eigenfunction \(\Psi\) satisfying
\[
R(\Psi) \subset \langle \eta \rangle.
\] (11.78)

**References**

[1] Bertolami O, Mourao J M, Picken R F and Volobuev I P 1991 Dynamics of Euclideanized Einstein Yang–Mills systems with arbitrary gauge groups Int. J. Mod. Phys. A 6 4149–80
[2] Casalbuoni R 1976 On the quantization of systems with anticommuting variables Il Nuovo Cimento A (1971–1976) 33 115–25
[3] Casalbuoni R 1976 The classical mechanics for Bose–Fermi systems Il Nuovo Cimento A (1971–1976) 33 389–431
[4] Dirac P A M 1958 *The Principles of Quantum Mechanics* 4th edn (Oxford: Clarendon) (reprinted in 1978)
[5] Eguchi T, Gilkey P B and Hanson A J 1980 Gravitation, gauge theories and differential geometry Phys. Rep. 66 213
[6] Faddeev L D and Slavnov A A 1980 *Gauge Fields* (Frontiers in Physics vol 50) (New York: Benjamin)
[7] Frankel T 2004 *The Geometry of Physics* 2nd edn (Cambridge: Cambridge University Press)
[8] Gerhardt C 1982 Abstract eigenvalue problems with applications to the eigenfunctions of the Laplace operator in compact manifolds, especially the sphere, spherical harmonics http://www.math.uni-heidelberg.de/ studinfo/gerhardt/Eigenwertprobleme.pdf, (pdf file of handwriten lecture notes in German)
[9] Gerhardt C 2009 Quantum cosmological Friedman models with a massive Yang–Mills field Class. Quantum Grav. 26 135013 (arXiv:0903.1370)
[10] Gerhardt C 2009 Quantum cosmological Friedman models with an initial singularity Class. Quantum Grav. 26 015001 (arXiv:0806.1769)
[11] Gerhardt C 2010 Quantum cosmological Friedman models with a Yang–Mills field and positive energy levels Class. Quantum Grav. 27 035007 (arXiv:0907.5403)
[12] Hardy G H, Littlewood J E and Pólya G 1973 *Inequalities* (Cambridge: Cambridge University Press)
[13] Moniz P V and Mourao J M 1991 Homogeneous and isotropic closed cosmologies with a gauge sector Class. Quantum Grav. 8 1815–31
[14] Thiemann T 1998 Kinematical Hilbert spaces for fermionic and Higgs quantum field theories Class. Quantum Grav. 15 1487–512
[15] Weinberg S 1967 A model of leptons Phys. Rev. Lett. 19 1264–6