

Elements of Geometric Quantization & Applications to Fields and Fluids

V.P. NAIR

Physics Department
City College of the CUNY
New York, NY 10031

E-mail: vpn@sci.ccny.cuny.edu

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How to read these notes

These notes are meant to give you a flavor of the material I shall discuss. I will not cover all sections here, there are a few topics which have been added for a better sense of completion. Some of it may be useful background or needed results or they provide an opening to interesting literature for those of you who might want to pursue related issues. There are also some practice problems at the end which may be helpful.

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1 Introduction

A physical theory, as a logical explanation of physical phenomena, is to be constructed taking account of general principles and incorporating data and information from experiments. Any effects we attribute to the quantum nature of phenomena should be included from the outset. A classical description may then be obtained, in a suitable regime of parameters, as a useful and simpler working approximation. The flow of logic should thus be

$$\left. \begin{array}{l} \text{General principles +} \\ \text{experimental input} \end{array} \right\} \implies \text{Quantum theory} \implies \text{Classical approximation}$$

But the build-up of a theory along these lines is almost never done in practice. Primarily, this is because, at the human level of direct experience, most phenomena are well described by classical dynamics, and hence our intuition about physical systems is mostly classical, and so we tend to start there and try to quantize the classical theory. This is a process with many ambiguities, but over the course of many years, we have learned to understand the structure of this procedure of quantization. In these lectures, I will attempt to describe some aspects of geometric quantization and consider a few examples or applications.

Quantum theory may be defined as a unitary irreducible representation (UIR) of the algebra of observables, the latter being selected by physical criteria. The algebra itself must satisfy certain conditions so as to have the correct physical requirements. Generally it ends up as a C^* -algebra with further additional conditions equivalent to symmetries (such as Lorentz invariance) and so on. We are not going to pursue such a line of development here. Instead, we will consider the essential geometry (which has to do with the symplectic structure) of the classical theory and work out how a quantum theory can be constructed. This will be done in the language of Hamiltonians and Hilbert space. There is yet another approach to the quantum theory, the functional integral approach, which is formulated directly in terms of the action and can be made manifestly covariant if the theory of interest has relativistic invariance. We will not discuss it here, but some points of overlap will be pointed out as the occasion arises.

2 Symplectic form and Poisson brackets

We start with the formulation of theories in the symplectic language [1, 2, 3]. Later, we will briefly discuss how this is connected to the action which may be used to specify the physical theory.

2.1 Symplectic structure

In the analytical formulation of classical physics, the key concept is the phase space, which is a smooth even dimensional manifold M endowed with a symplectic structure Ω . By this we mean that there is a differential 2-form Ω defined on M which is closed and nondegenerate. Closure means that $d\Omega = 0$. The qualification “nondegenerate” refers to the fact that for any vector field ξ on M , if $i_\xi\Omega = 0$ then ξ must be zero. In local coordinates q^μ , on M , we can write

$$\Omega = \frac{1}{2} \Omega_{\mu\nu} dq^\mu \wedge dq^\nu \quad (1)$$

The closure condition $d\Omega = 0$ can be written out as

$$\begin{aligned} d\Omega &\equiv \frac{\partial\Omega_{\mu\nu}}{\partial q^\alpha} dq^\alpha \wedge dq^\mu \wedge dq^\nu \\ &= \frac{1}{3} \left[\frac{\partial\Omega_{\mu\nu}}{\partial q^\alpha} + \frac{\partial\Omega_{\alpha\mu}}{\partial q^\nu} + \frac{\partial\Omega_{\nu\alpha}}{\partial q^\mu} \right] dq^\alpha \wedge dq^\mu \wedge dq^\nu \\ &= 0 \end{aligned} \quad (2)$$

The contraction of Ω with a vector field $\xi = \xi^\mu(\partial/\partial q^\mu)$ is given by

$$i_\xi\Omega = \xi^\mu \Omega_{\mu\nu} dq^\nu \quad (3)$$

Thus in terms of components, the equation $i_\xi\Omega = 0$ becomes $\xi^\mu \Omega_{\mu\nu} = 0$. Nondegeneracy of Ω is then seen to be equivalent to the invertibility of $\Omega_{\mu\nu}$ as a matrix, so that $\xi^\mu \Omega_{\mu\nu} = 0$ implies $\xi^\mu = 0$; in other words, $\Omega_{\mu\nu}$, viewed as a matrix, does not have an eigenstate of eigenvalue equal to zero.

The inverse of $\Omega_{\mu\nu}$, which will be needed for some equations, will be denoted by $\Omega^{\mu\nu}$, i.e.,

$$\Omega_{\mu\nu} \Omega^{\nu\alpha} = \delta_\mu^\alpha \quad (4)$$

For now, we will take Ω to be nondegenerate. There are cases where the action will lead to a degenerate $\Omega_{\mu\nu}$; this occurs when the theory has a gauge symmetry. Elimination of certain components of the gauge field via gauge-fixing is needed to define a nondegenerate Ω ; we will consider such cases briefly later. With the structure Ω defined on it, M is a symplectic manifold.

Since Ω is closed, at least locally we can write

$$\Omega = d\mathcal{A} \quad (5)$$

The one-form \mathcal{A} defined by this equation is called the canonical one-form or symplectic potential. There is an ambiguity in the definition of \mathcal{A} since \mathcal{A} and $\mathcal{A} + d\Lambda$ will give the same Ω

for any function Λ on M . As we shall see shortly, this corresponds to the freedom of canonical transformations.

There are two types of features associated with the topology of the phase space which are apparent at this stage. The first question is: Is every 2-form Ω which is closed (i.e., $d\Omega = 0$) the exterior derivative of a 1-form \mathcal{A} ? The set of linearly independent 2-forms which cannot be expressed as $d\mathcal{A}$ for some 1-form \mathcal{A} is the second cohomology group of the manifold M ; this is denoted by $\mathcal{H}^2(M)$. Thus, if the phase space M has nontrivial second cohomology, i.e., if $\mathcal{H}^2(M) \neq 0$, then there are possible choices for Ω for which there is no globally defined potential \mathcal{A} . There are examples of physical interest where this happens. They correspond to the Wess-Zumino terms in the action and are related to anomalies and also to central (and other) extensions of the algebra of observables.

Even when $\mathcal{H}^2(M) = 0$, there can be topological issues in defining \mathcal{A} . If the first cohomology $\mathcal{H}^1(M) \neq 0$, this means, by definition, that there are 1-forms A whose derivative is zero, but which are not of the form d of a function on M . Thus \mathcal{A} and $\mathcal{A} + A$ will give the same Ω , but the difference is not just $d\Lambda$ for some function Λ , since A does not have to be of the form $d\Lambda$, globally. In other words, there are inequivalent \mathcal{A} 's for the same Ω . In these cases, one can consider the integral of \mathcal{A} around closed noncontractible curves on M . The values of these integrals or holonomies will be important in the quantum theory as vacuum angles. The standard θ -vacuum of nonabelian gauge theories is an example. We take up these topological issues in more detail later.¹

Given the symplectic structure, transformations which preserve Ω are evidently special; these are called *canonical transformations*. In other words, a canonical transformation is a diffeomorphism (or coordinate transformation) of M which preserves Ω . Infinitesimally, the coordinate transformation may be taken to be $q^\mu \rightarrow q^\mu + \xi^\mu(q)$. The change in Ω due to this is given by

$$\begin{aligned}
\delta_\xi \Omega &= \frac{1}{2} \Omega_{\mu\nu}(q + \xi) d(q^\mu + \xi^\mu) \wedge d(q^\nu + \xi^\nu) - \frac{1}{2} \Omega_{\mu\nu} dq^\mu \wedge dq^\nu \\
&= \frac{1}{2} \left[\xi^\alpha \frac{\partial \Omega_{\mu\nu}}{\partial q^\alpha} + \Omega_{\alpha\nu} \frac{\partial \xi^\alpha}{\partial q^\mu} + \Omega_{\mu\alpha} \frac{\partial \xi^\alpha}{\partial q^\nu} \right] dq^\mu \wedge dq^\nu \\
&= \frac{1}{2} \xi^\alpha \left[\frac{\partial \Omega_{\mu\nu}}{\partial q^\alpha} + \frac{\partial \Omega_{\alpha\mu}}{\partial q^\nu} + \frac{\partial \Omega_{\nu\alpha}}{\partial q^\mu} \right] dq^\mu \wedge dq^\nu \\
&\quad + \frac{1}{2} [\partial_\mu(\xi^\alpha \Omega_{\alpha\nu}) - \partial_\nu(\xi^\alpha \Omega_{\alpha\mu})] dq^\mu \wedge dq^\nu \\
&= i_\xi(d\Omega) + d(i_\xi \Omega)
\end{aligned} \tag{6}$$

¹To be very specific, the cohomologies we are talking about are over \mathbb{R} , this refined statement will not be needed in much of what we discuss.

For a canonical transformation, this change must be zero.² Since $d\Omega = 0$, this means that canonical transformations are generated by vector fields ξ such that

$$d(i_\xi\Omega) = 0 \tag{7}$$

Thus for canonical transformations, $i_\xi\Omega$ is a closed 1-form. If the first cohomology $\mathcal{H}^1(M)$ of M is trivial, we can write

$$i_\xi\Omega = -df, \quad \xi^\alpha \Omega_{\alpha\nu} = -\frac{\partial f}{\partial q^\nu} \tag{8}$$

for some function f on M . In other words, to every infinitesimal canonical transformation, we can associate a function on M .³ Since Ω is invertible, we can always associate a vector field to a function f by the correspondence

$$\xi^\mu = \Omega^{\mu\nu} \partial_\nu f \tag{9}$$

What we are saying now is that, for a canonical transformation, we can go the other way, associating a function with the vector field which gives the canonical transformation, at least when $\mathcal{H}^1(M) = 0$. There is a one-to-one mapping between functions on M and vector fields corresponding to infinitesimal canonical transformations. A vector field corresponding to an infinitesimal canonical transformation is often referred to as a Hamiltonian vector field. The function f defined by (8) is called the generating function for the canonical transformation corresponding to the vector field.

It is important that for every function f on the phase space M , we can associate a Hamiltonian vector field as in (11). This means that all observables which are functions on M generate canonical transformations.

2.2 Poisson brackets

Let ξ, η be two Hamiltonian vector fields which means that they preserve Ω ; let their generating functions be f and g respectively. The Lie bracket or commutator of ξ and η is given in local coordinates by

$$[\xi, \eta]^\mu = \xi^\nu \partial_\nu \eta^\mu - \eta^\nu \partial_\nu \xi^\mu \tag{10}$$

We can easily verify that the commutator will also preserve Ω . We must therefore have a function corresponding to $[\xi, \eta]$. This is called the Poisson bracket of g and f and is denoted by $\{g, f\}$. We

²The right hand side of (6) is the Lie derivative of Ω with respect to the vector field $\xi^\alpha(\partial/\partial q^\alpha)$. We will not use this terminology to avoid introducing too many definitions.

³If $\mathcal{H}^1(M) \neq 0$, then there is the possibility that for some transformations ξ , the corresponding $i_\xi\Omega$ is a nontrivial element of $\mathcal{H}^1(M)$ and hence there is no globally defined function f for this transformation. As mentioned before this is related to the possibility of vacuum angles in the quantum theory. For the moment, we shall consider the case $\mathcal{H}^1(M) = 0$.

define the Poisson bracket as

$$\begin{aligned}
\{f, g\} &= i_\xi i_\eta \Omega = \eta^\mu \xi^\nu \Omega_{\mu\nu} \\
&= -i_\xi dg = i_\eta df \\
&= \Omega^{\mu\nu} \partial_\mu f \partial_\nu g
\end{aligned} \tag{11}$$

Notice that, for the choice $f = q^\mu$, $g = q^\nu$, this reduces to

$$\{q^\mu, q^\nu\} = \Omega^{\mu\nu} \tag{12}$$

Because of the antisymmetry of $\Omega_{\mu\nu}$, the Poisson bracket has the property

$$\{f, g\} = -\{g, f\} \tag{13}$$

Further, from the definition, we can write, using local coordinates,

$$\begin{aligned}
2 \partial_\alpha \{f, g\} &= \partial_\alpha (\eta \cdot \partial f - \xi \cdot \partial g) \\
&= \partial_\alpha \eta^\mu \partial_\mu f + \eta^\mu (\partial_\mu \partial_\alpha f) - \partial_\alpha \xi^\mu \partial_\mu g - \xi^\mu (\partial_\mu \partial_\alpha g) \\
&= \partial_\alpha \eta^\mu \partial_\mu f - \partial_\alpha \xi^\mu \partial_\mu g + \eta \cdot \partial (\xi^\mu \Omega_{\alpha\mu}) - \xi \cdot \partial (\eta^\mu \Omega_{\alpha\mu}) \\
&= \partial_\alpha \eta^\mu \partial_\mu f - \partial_\alpha \xi^\mu \partial_\mu g + (\xi \cdot \partial \eta - \eta \cdot \partial \xi)^\mu \Omega_{\mu\alpha} \\
&\quad + \eta^\mu \xi^\nu (\partial_\mu \Omega_{\alpha\nu} + \partial_\nu \Omega_{\mu\alpha}) \\
&= [\xi, \eta]^\mu \Omega_{\mu\alpha} + \partial_\alpha (\eta^\mu \xi^\nu \Omega_{\mu\nu}) + \eta^\mu \xi^\nu (\partial_\mu \Omega_{\alpha\nu} + \partial_\nu \Omega_{\mu\alpha} + \partial_\alpha \Omega_{\nu\mu})
\end{aligned} \tag{14}$$

In local coordinates, the closure of Ω is the statement $\partial_\mu \Omega_{\alpha\nu} + \partial_\nu \Omega_{\mu\alpha} + \partial_\alpha \Omega_{\nu\mu} = 0$. We then see that

$$-d\{g, f\} = i_{[\xi, \eta]} \Omega \tag{15}$$

which shows the correspondence stated earlier.

Consider now the change in a function F due to a canonical transformation $q^\mu \rightarrow q^\mu + \xi^\mu$. Let f be the function corresponding to ξ^μ via the correspondence (8). The change in F is obviously $\xi^\mu \partial_\mu F$. We can write this as

$$\delta F = \xi^\mu \partial_\mu F = (\Omega^{\mu\alpha} \partial_\alpha f) \partial_\mu F = \{F, f\} \tag{16}$$

Thus the change in a function F due to $q^\mu \rightarrow q^\mu + \xi^\mu$ is given by the Poisson bracket of F with the generating function f corresponding to ξ .

Another important property of the Poisson bracket is the Jacobi identity for any three functions f, g, h ,

$$\{f, \{g, h\}\} + \{h, \{f, g\}\} + \{g, \{h, f\}\} = 0 \tag{17}$$

This can be verified by direct computation from the definition of the Poisson bracket. In fact, if ξ, η, ρ are the Hamiltonian vector fields corresponding to the functions f, g, h , then, by direct computation,

$$\{f, \{g, h\}\} + \{h, \{f, g\}\} + \{g, \{h, f\}\} = -i_{\xi}i_{\eta}i_{\rho}(d\Omega) \quad (18)$$

and so the Jacobi identity (17) follows from the closure of Ω .

An expression which will be useful later is the change of the symplectic potential \mathcal{A} under an infinitesimal canonical transformation; this can be worked out as

$$\begin{aligned} \delta_{\xi}\mathcal{A} &= \mathcal{A}_{\mu}(q + \xi)dq^{\mu} - \mathcal{A}_{\mu}(q)dq^{\mu} = \left[\xi^{\alpha}\partial_{\alpha}\mathcal{A}_{\mu} + \mathcal{A}_{\alpha}\frac{\partial\xi^{\alpha}}{\partial q^{\mu}} \right] dq^{\mu} \\ &= [\xi^{\alpha}(\partial_{\alpha}\mathcal{A}_{\mu} - \partial_{\mu}\mathcal{A}_{\alpha}) + \partial_{\mu}(\xi^{\alpha}\mathcal{A}_{\alpha})] dq^{\mu} \\ &= [\xi^{\alpha}\Omega_{\alpha\mu} + \partial_{\mu}(\xi^{\alpha}\mathcal{A}_{\alpha})] dq^{\mu} \\ &= \partial_{\mu}(\xi^{\alpha}\mathcal{A}_{\alpha} - f) dq^{\mu} \end{aligned} \quad (19)$$

where we used the definition of Ω and the fact that ξ is a Hamiltonian vector field with a corresponding function f defined by equation (8). Equation (19) shows that under a canonical transformation $\mathcal{A} \rightarrow \mathcal{A} + d\Lambda$, $\Lambda = i_{\xi}\mathcal{A} - f$. Evidently $d\mathcal{A} = \Omega$ is unchanged under such a transformation. This suggests a very useful way of thinking about these structures.

We may view \mathcal{A} as a $U(1)$ gauge potential and Ω as the corresponding field strength. The transformation $\mathcal{A} \rightarrow \mathcal{A} + d\Lambda$ is thus a gauge transformation. We can use this to construct an invariant description, using covariant derivatives and other properly transforming quantities.

A remark which may be useful in comparing the symplectic language we have used to some other formulations: If we use the definition of the Poisson bracket, namely (11), for the phase space coordinates themselves, we have equation (12), $\{q^{\mu}, q^{\nu}\} = \Omega^{\mu\nu}$. This is often interpreted as saying that the ‘‘basic Poisson brackets’’ (i.e., PBs for the phase space coordinates themselves) are the inverse of the symplectic structure.

2.3 Phase volume

The symplectic two-form can be used to define a volume form on the phase space M by

$$d\sigma(M) = c \frac{\Omega \wedge \Omega \wedge \dots \wedge \Omega}{(2\pi)^n} = c \sqrt{\det\left(\frac{\Omega}{2\pi}\right)} d^{2n}q \quad (20)$$

where we take the n -fold product of Ω 's for a $2n$ -dimensional phase space. (c is a constant which is undetermined at this stage.) If the dimension of the phase space is infinite, then a suitable regularized form of the determinant of $\Omega_{\mu\nu}$ has to be used. The volume measure defined by equation (20) is called the Liouville measure.

2.4 Darboux's theorem

A useful result concerning the symplectic form is Darboux's theorem which states that in the neighbourhood of a point on the phase space it is possible to choose coordinates p_i, x^i , $i = 1, 2, \dots, n$, (which are functions of the coordinates q^μ we started with) such that the symplectic two-form is

$$\begin{aligned}\Omega &= dp_i \wedge dx^i = \frac{1}{2} J_{\mu\nu} dQ^\mu \wedge dQ^\nu \\ Q^\mu &= (p_1, x^1, p_2, x^2, \dots, p_n, x^n)\end{aligned}\tag{21}$$

The tensor $J_{\mu\nu}$ (which is $\Omega_{\mu\nu}$ in these coordinates) can be expressed in matrix form as

$$J_{\mu\nu} = \begin{bmatrix} 0 & 1 & 0 & 0 & \dots \\ -1 & 0 & 0 & 0 & \dots \\ 0 & 0 & 0 & 1 & \dots \\ 0 & 0 & -1 & 0 & \dots \\ \dots & \dots & \dots & \dots & \dots \end{bmatrix}\tag{22}$$

Evidently from the form of Ω , we see that the Poisson brackets in terms of this set of coordinates are

$$\begin{aligned}\{x^i, x^j\} &= 0 \\ \{x^i, p_j\} &= \delta_j^i \\ \{p_i, p_j\} &= 0\end{aligned}\tag{23}$$

We will not consider the proof of Darboux's theorem here, although it is not very complicated. A simple and elegant argument can be found in Arnold's book [1].

3 Classical dynamics

The importance of the symplectic approach is that, classically, the time-evolution of any quantity is a particular canonical transformation generated by a function H called the Hamiltonian.

This is the essence of the Hamiltonian formulation of dynamics. Thus if F is any function on M , we then have

$$\frac{\partial F}{\partial t} = \{F, H\} \quad (24)$$

Specifically for the local coordinates q^μ on M this equation leads to

$$\frac{\partial q^\mu}{\partial t} = \{q^\mu, H\} = \Omega^{\mu\nu} \frac{\partial H}{\partial q^\nu} \quad (25)$$

Since Ω is invertible, we can also write this equation as

$$\Omega_{\mu\nu} \frac{\partial q^\nu}{\partial t} = \frac{\partial H}{\partial q^\mu} \quad (26)$$

If we use the Darboux coordinates (p_i, x^i) , these equations (either (25) or (26)) become

$$\dot{p}_i = -\frac{\partial H}{\partial x^i}, \quad \dot{x}^i = \frac{\partial H}{\partial p_i} \quad (27)$$

which are more easily recognizable as Hamilton's canonical equations.

We are now in a position to connect the dynamics to an action and a variational principle. We *define* the action as

$$\mathcal{S} = \int_{t_i}^{t_f} dt \left(\mathcal{A}_\mu \frac{dq^\mu}{dt} - H \right) \quad (28)$$

where $q^\mu(t)$ gives a path on M . Under a general variation of the path $q^\mu(t) \rightarrow q^\mu(t) + \xi^\mu(t)$, the action changes by

$$\begin{aligned} \delta \mathcal{S} &= \int dt \left(\frac{\partial \mathcal{A}_\nu}{\partial q^\mu} \frac{dq^\nu}{dt} \xi^\mu + \mathcal{A}_\mu \frac{d\xi^\mu}{dt} - \frac{\partial H}{\partial q^\mu} \xi^\mu \right) \\ &= \left. \mathcal{A}_\mu \xi^\mu \right]_{t_i}^{t_f} + \int dt \left(\Omega_{\mu\nu} \frac{dq^\nu}{dt} - \frac{\partial H}{\partial q^\mu} \right) \xi^\mu \end{aligned} \quad (29)$$

The variational principle says that the equations of motion are given by the extremization of the action, i.e., by $\delta \mathcal{S} = 0$, for restricted set of variations with the boundary data (initial and final end point data) fixed. From the above variation, we see that this gives the Hamiltonian equations of motion (26). There is a slight catch in this argument because q^μ are phase space coordinates and obey first order equations of motion. So we can only specify the initial value of q^μ . However, the Darboux theorem tells us that one can choose coordinates on M such that the canonical one-form \mathcal{A} is of the form $p_i dx^i$. The ξ^μ in the boundary term is just δx^i . Therefore, instead of specifying initial data for all q^μ , we can choose to specify initial and final data for the x^i 's. Since the boundary values are to be kept fixed in the variational principle $\delta \mathcal{S} = 0$, we may set $\delta x^i = 0$ at both boundaries and the equations of motion are indeed just (26).

We have shown how to define the action if Ω is given. However, going back to the general variations, notice that the boundary term resulting from the time-integration is just the canonical one-form contracted with ξ^μ . Thus if we start from the action as the given quantity, we can identify the canonical one-form and hence Ω from the boundary term which arises in a general variation. In fact

$$\delta\mathcal{S} = i_\xi\mathcal{A}(t_f) - i_\xi\mathcal{A}(t_i) + \int dt \left(\Omega_{\mu\nu} \frac{dq^\nu}{dt} - \frac{\partial H}{\partial q^\mu} \right) \xi^\mu \quad (30)$$

As an example of this, consider a real scalar field theory with the action

$$\mathcal{S} = \int d^4x \left[\frac{1}{2}\dot{\varphi}^2 - \frac{1}{2}(\nabla\varphi)^2 - \frac{1}{2}m^2\varphi^2 - \alpha\varphi^4 \right] \quad (31)$$

The variation of the action leads, upon time-integration, to the boundary term

$$\delta\mathcal{S} = \int d^3x \dot{\varphi} \delta\varphi \Big|_{t_i}^{t_f} + \int d^4x [\dots] \quad (32)$$

The canonical 1-form or the symplectic potential (at a fixed time t) can thus be taken as

$$\mathcal{A} = \int d^3x \dot{\varphi} \delta\varphi \quad (33)$$

In this analysis, we are at a fixed time, so $\dot{\varphi}$ is a function independent of φ . The phase space thus consists of the set of functions $\{\dot{\varphi}, \varphi\}$ on the three-dimensional space \mathbb{R}^3 . \mathcal{A} in (33) is a 1-form on the phase space, interpreting $\delta\varphi$ (which is a functional variation) as the exterior derivative on the space of fields.

If we add a total derivative to the Lagrangian, say, $\mathcal{S} \rightarrow \mathcal{S} + \int dt f$, it does not affect the equations of motion. However, the new \mathcal{A} obtained from the boundary values has an extra term δf . This is the exterior derivative of f and hence the symplectic two-form Ω (which is $\delta\mathcal{A}$) is unchanged. We see that the freedom of adding total derivatives to the Lagrangian is thus the freedom of canonical transformations.

An interesting variant for the scalar field theory is to consider the light-cone quantization of the same theory. Introduce light-cone coordinates, corresponding to a light-cone in the z -direction, as

$$u = \frac{1}{\sqrt{2}}(t + z), \quad v = \frac{1}{\sqrt{2}}(t - z) \quad (34)$$

Instead of considering evolution of the fields in time t , we can consider evolution in one of the light-cone coordinates, say, u . The analog of ‘space’ is given by the other light-cone coordinate v and the two coordinates $x^T = x, y$ transverse to the light-cone. They correspond to equal- u hypersurfaces. The action (31) for the real scalar field $\varphi(u, v, x, y)$ can be written in these coordinates as

$$\mathcal{S} = \int du dv d^2x^T \left[\partial_u\varphi\partial_v\varphi - \frac{1}{2}(\partial_T\varphi)^2 - \frac{1}{2}m^2\varphi^2 - \alpha\varphi^4 \right] \quad (35)$$

This is first order in the u -derivatives, the analog of the time-derivatives. The time-integration of the variation of this action leads to the boundary term

$$\delta\mathcal{S} = \int dv d^2x^T \left. \partial_v \varphi \delta\varphi \right]_{u_i}^{u_f} + \text{volume integral} \quad (36)$$

Since $\partial_v \varphi$ is a spatial derivative now, it is not independent of φ and so the phase space is given by field configurations $\varphi(v, x^T)$. The symplectic potential is

$$\mathcal{A} = \int dv d^2x^T \partial_v \varphi \delta\varphi \quad (37)$$

We will consider other cases of determining the symplectic form using this method when we take up examples.

4 Geometric quantization

Quantum theory of any physical system is a unitary irreducible representation of the algebra of observables of the system. This means that the observables are realized as linear operators on a Hilbert space. The allowed transformation of variables are then unitary transformations. There are thus two key points regarding quantization:

1. We need a correspondence between canonical transformations and unitary transformations
2. We must ensure that the representation of unitary transformations on the Hilbert space is irreducible.

Since functions on phase space generate canonical transformations and hermitian operators generate unitary transformations, the first point is that we get a correspondence between functions on phase space and operators on the Hilbert space. The algebra of Poisson brackets will be replaced by the algebra of commutation rules. The irreducibility leads to the necessity of choosing a polarization for the wave functions.

4.1 Pre-quantization

We will first consider the notion of the wave function before discussing how operators act on such wave functions. In the geometric approach, the first step is the so-called prequantum line bundle.

This is a complex line bundle on the phase space with curvature Ω . Sections of this line bundle form the prequantum Hilbert space. In less technical terms, we utilize the similarity we mentioned earlier, namely, that the symplectic potential may be thought of as a $U(1)$ gauge field, with the transformations $\mathcal{A} \rightarrow \mathcal{A} + d\Lambda$ viewed as a gauge transformation. We can then consider complex functions $\Psi(q)$ defined on open neighborhoods in M . These are like matter fields, they are the sections of the line bundle. This means that locally they are complex functions which transform as

$$\Psi \rightarrow \Psi' = \exp(i\Lambda) \Psi \quad (38)$$

We can define a covariant derivative acting on $\Psi(q)$ using \mathcal{A} as

$$\mathcal{D}_\mu \Psi \equiv \left(\frac{\partial}{\partial q^\mu} - i\mathcal{A}_\mu \right) \Psi \quad (39)$$

The commutator of two covariant derivatives gives $-i\Omega$, this is the meaning of saying that the curvature of the line bundle is Ω .

Since canonical transformations correspond to $\mathcal{A} \rightarrow \mathcal{A} + d\Lambda$, the transformation of Ψ as given in (38) is equivalent to the requirement of canonical transformations being implemented as unitary transformations. The transition rules for the Ψ 's from one patch on M to another are likewise given by exponentiating the transition function for \mathcal{A} . The functions Ψ 's so defined form the prequantum Hilbert space with the inner product

$$(1|2) = \int d\sigma(M) \Psi_1^* \Psi_2 \quad (40)$$

where $d\sigma(M)$ is the Liouville measure on the phase space defined by Ω .

We now turn to operators (acting on Ψ) corresponding to various functions on the phase space. A function $f(q)$ on the phase space generates a canonical transformation which leads to the change $\Lambda = i_\xi \mathcal{A} - f$ in the symplectic potential, see (19). The corresponding change in Ψ is thus

$$\begin{aligned} \delta\Psi &= \xi^\mu \partial_\mu \Psi - i(i_\xi \mathcal{A} - f)\Psi \\ &= \xi^\mu (\partial_\mu - i\mathcal{A}_\mu) \Psi + if\Psi \\ &= (\xi^\mu \mathcal{D}_\mu + if) \Psi \end{aligned} \quad (41)$$

where the first term on the right hand side in the first line gives the change in Ψ considered as a function and the second term compensates for the change of \mathcal{A} . The change can be expressed using the covariant derivative as in the last line. Given (41), it is natural to define the *prequantum operator* corresponding to $f(q)$ by

$$\mathcal{P}(f) = -i(\xi \cdot \mathcal{D} + if) \quad (42)$$

We can easily check that

$$\int d^{2n}q \sqrt{\det \Omega} \Psi_1^* [\mathcal{P}(f) \Psi_2] = \int d^{2n}q \sqrt{\det \Omega} [\mathcal{P}(f) \Psi_1]^* \Psi_2 \quad (43)$$

so that $\mathcal{P}(f)$ is a symmetric operator, which is necessary condition for a unitary representation. (Strictly speaking, before we can claim a unitary representation, we need to consider the completion of the set of such functions and also make sure the domains and ranges of operators match; we will not go into this question, since the whole issue has to be addressed for the true wave functions anyway.)

Now consider the algebra of the prequantum operators. We have already seen in (15) that if the Hamiltonian vector fields for f, g are ξ and η respectively, then the vector field corresponding to the Poisson bracket $\{f, g\}$ is $-\xi, \eta$. Using the definition of the prequantum operator above, we then find

$$\begin{aligned} [\mathcal{P}(f), \mathcal{P}(g)] &= [-i\xi \cdot \mathcal{D} + f, -i\eta \cdot \mathcal{D} + g] \\ &= -[\xi^\mu \mathcal{D}_\mu, \eta^\nu \mathcal{D}_\nu] - i\xi^\mu [\mathcal{D}_\mu, g] + i\eta^\mu [\mathcal{D}_\mu, f] \\ &= i\xi^\mu \eta^\nu \Omega_{\mu\nu} - (\xi^\mu \partial_\mu \eta^\nu) \mathcal{D}_\nu + (\eta^\mu \mathcal{D}_\mu \xi^\nu) \mathcal{D}_\nu - i\xi^\mu \partial_\mu g + i\eta^\mu \partial_\mu f \\ &= i(-\xi^\mu \eta^\nu \Omega_{\mu\nu} + i[\xi, \eta] \cdot \mathcal{D}) \\ &= i(-i(i_{[\eta, \xi]} \mathcal{D}) + \{f, g\}) \\ &= i\mathcal{P}(\{f, g\}) \end{aligned} \quad (44)$$

In other words, the prequantum operators form a representation of the Poisson bracket algebra of functions on phase space.

4.2 Polarization

It seems like we have all the ingredients for the quantum theory, but not quite so. The prequantum wave functions Ψ depend on all phase space variables. The representation of the Poisson bracket algebra on such wave functions, given by the prequantum operators, is reducible. We will use a simple example to illustrate this point.

Consider a point particle in one dimension, with the symplectic two-form $\Omega = dp \wedge dx$. We can choose $\mathcal{A} = p dx$. The vector fields corresponding to x and p are $\xi_x = -\partial/\partial p$ and $\xi_p = \partial/\partial x$. The corresponding prequantum operators are

$$\mathcal{P}(x) = i\frac{\partial}{\partial p} + x, \quad \mathcal{P}(p) = -i\frac{\partial}{\partial x} \quad (45)$$

which obey the commutation rule

$$[\mathcal{P}(x), \mathcal{P}(p)] = i \quad (46)$$

We have a representation of the algebra of $\mathcal{P}(x), \mathcal{P}(p)$ in terms of the prequantum wave functions $\Psi(x, p)$. But this is reducible. For if we consider the subset of functions on the phase space which are independent of p , namely those which obey the condition

$$\frac{\partial \Psi}{\partial p} = 0, \quad (47)$$

then the prequantum operators reduce to

$$\mathcal{P}(x) = x, \quad \mathcal{P}(p) = -i \frac{\partial}{\partial x} \quad (48)$$

which obey the same algebra (46). Thus we are able to obtain a representation of the algebra of observables on the smaller space of Ψ 's obeying the constraint (47), showing that the previous representation (45) is reducible.

In order to obtain an irreducible representation, one has to impose subsidiary conditions which restrict the dependence of the prequantum wave functions to half the number of phase space variables. This is the choice of polarization and generally leads to an irreducible representation of the Poisson algebra.

If we are talking about ordinary functions f on the phase space M , the statement that f is independent of n of the coordinates can be phrased as

$$P_i^\mu \frac{\partial f}{\partial q^\mu} = 0 \quad (49)$$

where $P_i = P_i^\mu (\partial/\partial q^\mu)$, $i = 1, 2, \dots, n$, form n linearly independent vector fields. An integrability requirement for (49) is

$$[P_i, P_j]^\mu \frac{\partial f}{\partial q^\mu} = 0 \quad (50)$$

which can be ensured if

$$[P_i, P_j] = C_{ij}^k P_k \quad (51)$$

where the coefficients C_{ij}^k need not be constants. If we have a set of vector fields P_i obeying (51), then they are said to be in involution. If this is satisfied, we can integrate, starting from some point on M , along these vector fields and obtain, at least locally, a neighborhood of an n -dimensional submanifold. (This is ensured by Frobenius' theorem.) Such a submanifold is said to be a Lagrangian submanifold if we also have the condition

$$\Omega_{\mu\nu} P_i^\mu P_j^\nu = 0 \quad (52)$$

The prequantum wave functions are not functions on M , they are sections of a line bundle, i.e., they transform with a phase under $\mathcal{A} \rightarrow \mathcal{A} + d\Lambda$, and so we must impose the covariant version of (49). Thus, as the polarization condition we choose

$$P_i^\mu \mathcal{D}_\mu \Psi = 0 \quad (53)$$

where P_i are n linearly independent vector fields obeying (51) and (52). The integrability requirement for (53) is automatically satisfied since

$$\begin{aligned} [P_i^\mu \mathcal{D}_\mu, P_j^\nu \mathcal{D}_\nu] \Psi &= C_{ij}^k P_k^\mu \mathcal{D}_\mu \Psi - i \Omega_{\mu\nu} P_i^\mu P_j^\nu \Psi \\ &= 0 \end{aligned} \quad (54)$$

by virtue of (53) and (52). The prequantum wave functions restricted by the polarization condition (53) are the true wave functions of the theory. There can be different possible choices for the polarization leading to wave functions depending on different subsets of phase space coordinates. For example, the difference between the momentum space wave functions and the coordinate space wave functions familiar from elementary quantum mechanics is one of different polarization choices.

4.3 Measure of integration

The next step is to define an inner product to make these wave functions into a Hilbert space. Obviously, if the wave functions do not depend on half the number of phase space coordinates, it does not make sense to integrate over them in an inner product. In particular, it would give an undefined or infinite value if those directions do not have a finite volume. So one needs to define a volume measure for integration over the coordinates on which the wave functions do depend. The problem is that while the Liouville measure for all of phase space is naturally defined in terms of the symplectic structure, there is no natural choice of integration measure for the reduced set of variables, once we impose the polarization requirement. In many cases, the phase space is the cotangent bundle of some manifold (which is the configuration space Q), which means that it is made of the coordinates and co-vectors. For example, for particle dynamics on $Q = \mathbb{R}^3$, $M = T^*\mathbb{R}^3$ which has coordinates x^μ and momenta p_μ as the basic coordinates. Then, if we use a polarization given by $P_i^\mu = (\partial/\partial p_\mu)$, the wave functions depend on x only. This is the usual coordinate space Schrödinger quantum mechanics and one can use the integration just on \mathbb{R}^3 to form the inner product. But generally speaking, unless M is the cotangent bundle of some manifold, finding a reduced integration measure is not trivial.

However there is one case where there is a natural inner product on the Hilbert space. This happens when the phase space is also Kähler and Ω is the Kähler form or some multiple thereof.

In this case we can introduce local complex coordinates and write

$$\Omega = \Omega_{a\bar{a}} dz^a \wedge d\bar{z}^{\bar{a}} \quad (55)$$

$a, \bar{a} = 1, 2, \dots, n$. The corresponding covariant derivatives are

$$\mathcal{D}_a = \partial_a - i\mathcal{A}_a, \quad \mathcal{D}_{\bar{a}} = \partial_{\bar{a}} - i\mathcal{A}_{\bar{a}} \quad (56)$$

The characteristic of a Kähler manifold is the existence of a Kähler potential K such that

$$\mathcal{A}_a = -\frac{i}{2}\partial_a K, \quad \mathcal{A}_{\bar{a}} = \frac{i}{2}\partial_{\bar{a}} K \quad (57)$$

In this case, one can choose the holomorphic polarization

$$\mathcal{D}_{\bar{a}}\Psi = (\partial_{\bar{a}} + \frac{1}{2}\partial_{\bar{a}}K)\Psi = 0 \quad (58)$$

The solutions are the polarized wave functions ψ given by

$$\psi = \exp(-\frac{1}{2}K) F \quad (59)$$

where F is a holomorphic function on M . The wave functions are thus holomorphic, apart from the prefactor involving the Kähler potential. In this case, ψ^* involves the antiholomorphic functions F^* and the product depends on all the phase space coordinates. Integration over all of phase space is acceptable and the inner product of the prequantum Hilbert space can be retained, may be up to a constant of proportionality, as the inner product of the true Hilbert space; specifically we have

$$\langle 1|2 \rangle = \int d\sigma(M) e^{-K} F_1^* F_2 \quad (60)$$

The cases where $M = T^*Q$ for some manifold Q and the Kähler case will cover most of the physical situations of interest to us.

4.4 Representation of operators

Once the polarized wave functions are defined, the idea is to represent observables as linear operators on the wave functions as given by the prequantum differential operators. Let ξ be the Hamiltonian vector field corresponding to a function $f(q)$. If the commutator of ξ with any polarization vector field P_i is proportional to P_i itself, i.e., $[\xi, P_i] = C_i^j P_j$ for some functions C_i^j , then, evidently, ξ does not change the polarization; $\xi\Psi$ will obey the same polarization condition as Ψ . In this case the operator corresponding to $f(q)$ is given by $\mathcal{P}(f)$, but, of course, now acting on the wave functions in the chosen polarization.

The situation with operators which do not preserve the polarization is more complicated. There are many such operators of interest in any physical problem. For example, the Hamiltonian for a free nonrelativistic particle in one spatial dimension is $H = p^2/2m$, with the vector field $\xi_H = (p/m) (\partial/\partial x)$. If we choose the polarization which gives wave functions depending on x , namely, choose $P = (\partial/\partial p)$, then we find

$$[\xi_H, P] = -\frac{1}{m} \frac{\partial}{\partial x} \quad (61)$$

We see that ξ_H does not preserve the polarization. The solution is also suggested by this example. We can define p^2 trivially by using the momentum-space wave functions, namely, ones corresponding to the polarization $(\partial/\partial x)$. It is possible to transform from one type of wave functions to the other, in this case, by Fourier transformation. More generally, there are kernels, known as Blattner-Kostant-Sternberg (BKS) kernels, which map from one polarization to another. Using this, we can define operators as follows. We carry out a canonical transformation on the wave functions by the vector field $t \xi_f$ where f is the function whose operator version we wish to find and t is a real parameter. The result is no longer in the same polarization, but we can transform back using an appropriate BKS kernel. The derivative of the result with respect to t at $t = 0$ will give the action of the operator. Equivalently, we can work out the form of the operator in a polarization which is preserved by the corresponding vector field and then transform to the required polarization using an appropriate BKS kernel.

4.5 Comments on the measure of integration, corrected operators, etc.

The problem of defining the measure of integration in a given polarization has implications, which necessitates a certain modified definition for operators. Fortunately, this will not be an issue for most of what we want to do, but, nevertheless, a comment is in order at this stage. (For more detailed analysis, see [2, 4, 5].) To illustrate the problem, consider how we can show that $\mathcal{P}(f)$ is a symmetric operator, as in (43). The relevant partial integration leads to a discrepancy $\partial_\mu \xi^\mu + \frac{1}{2} \xi^\mu \partial_\mu (\log \det \Omega)$ which is zero by virtue of the closure of Ω and ξ being a Hamiltonian vector field. However, the integration measure for the polarized wave functions is not given by Ω and hence this argument does not go through. Consider a real polarization and let the inner product be of the form

$$\langle 1|2 \rangle = \int d^n x J \psi_1^* \psi_2 \quad (62)$$

(We do not necessarily mean that x denotes coordinates of some configuration space, it is used as a generic notation here.) We then find

$$\int \psi_1^* (\mathcal{P}(f)\psi_2) - \int (\mathcal{P}(f)\psi_1)^* \psi_2 = i \int d^n x J [\partial \cdot \xi + \xi \cdot \partial \log J] \psi_1^* \psi_2 \quad (63)$$

Clearly using $\mathcal{P}(f)$ to act on the polarized wave functions will not do. One strategy is to factorize J as $\bar{\sigma} \sigma$ where σ need not be real and consider $\psi \sigma$ in place of the wave function. The quantity σ behaves as the square root of the integration measure on the complement of the subspace defined by the polarization vector fields. For this reason, this way of considering $\psi \sigma$ directly, rather than ψ and then the measure of integration separately, is called the half-form quantization. We then modify the definition of the operator corresponding to f as ⁴

$$\begin{aligned}\mathcal{P}(f) \psi \sigma &= [(-i\xi \cdot \mathcal{D} + f) \psi] \sigma - \psi (iL_\xi \sigma) \\ L_\xi \sigma &= -i\xi \cdot \sigma - \frac{i}{2} \partial \cdot \xi \sigma\end{aligned}\tag{64}$$

With this definition, we can verify that

$$\int d^n x \psi^* \bar{\sigma} [\mathcal{P}(f) \psi \sigma] = \int d^n x [\mathcal{P}(f) \psi \sigma]^* \psi \sigma\tag{65}$$

It is useful to consider the problem of the integration measure in some more detail. For this purpose, let us consider the Lagrangian submanifold defined by the polarization $\{P_i\}$. Let u^i denote the local coordinates on this submanifold. The coordinates q^μ on the submanifold can be considered as functions of u^i and obey equations of the form

$$(E^{-1})_i^k \frac{\partial q^\mu}{\partial u^k} = P_i^\mu\tag{66}$$

The matrix of functions E_i^k plays the role of frame fields for the subspace and we can define a volume measure of the form $(\det E) d^n u$. In the inner product (62), the integrand $\psi_1^* \psi_2$ is independent of u^i . So, just as we do in the case of the functional integral for gauge theories, we can introduce a constraint $\delta^{(n)}(u) \det E^{-1}$ and integrate with the full Liouville measure. This will effectively remove the volume element $\det E d^n u$ of the Lagrangian submanifold from the Liouville volume element. But notice that if we make a transformation $P_i \rightarrow C_i^j P_j$ on the basis of polarization vectors, $\det E^{-1} \rightarrow (\det C) \det E^{-1}$. Thus the reduced volume must have this transformation property. In order to make this work for all polarizations, including holomorphic (or partly holomorphic) ones, we have to factorize $\det E^{-1}$ and hence we must consider quantities transforming as $(\det C)^{1/2}$. This may be formalized in terms of what is called the metaplectic structure. We consider a vector space V which can eventually be identified as the tangent bundle of M . Let $F \subset V$ be a subspace of V , and further, let X_a be a basis for F . (We may think of F as being defined by the set of polarization vectors with $X_a \sim P_a$.) We then consider quantities $\sigma_r(X_a)$ which depend on the basis and which has the property that $\sigma_r(X_a) \in \mathbb{C}$ and

$$\sigma_r(C_a^b X_b) = (\det C)^r \sigma_r(X_a)\tag{67}$$

⁴ $L_\xi \sigma$ is again the Lie derivative of σ .

If V is the tangent bundle, we can do this at every point on M , thereby defining a bundle which we will designate as $\delta_r(F)$, sections of which are σ_r . If $r = 1$ we are effectively talking about the volume element for F . For $r = \frac{1}{2}$, $\delta_{1/2}$ is a line bundle over M ; this is called a metaplectic structure on M . We may think of it as defining a volume on spinor frames. The volume for the polarized subspace may be defined using $\delta_{-1/2}(P)$ and $\delta_{-1/2}(\bar{P})$ acting on $\delta_1(M)$. Let $W = (P \cup \bar{P}) / (P \cap \bar{P})$. This can be shown to be a symplectic space with its own volume measure which will transform as σ_1 . The general formula for the required integration measure is then

$$d\mu = \sigma_{-1/2}(P) \sigma_{-1/2}(\bar{P}) \sigma_1(W) d\sigma(M) \quad (68)$$

For a real polarization, $P = \bar{P}$ and W is empty. Thus we get the result $\sigma_{-1}(P) d\sigma(M)$ which is the same as (62). The formula (68) factors out the effect of the directions defined by P . The two factors $\sigma_{-1/2}(P)$ and $\sigma_{-1/2}(\bar{P})$, which we denoted by σ and $\bar{\sigma}$ in equations (64) and (65), are needed for the action of the operators as in (64)⁵ In the integration measure, we can go back to the form $\delta^{(n)}(u) \det E^{-1}$ which is given by $\sigma_1(P)$. If we consider holomorphic polarization, then $P \cup \bar{P} = M$ and $P \cap \bar{P} = \emptyset$, so that we get $\sigma_1(W) = \sigma_1(M)$ gives another factor of $\det \Omega$. This cancels with the $\sigma_{-1/2}$ factors retaining $d\sigma(M)$ as the volume. However, the definition of operators will have the corrections from $L_\xi \sigma_{-1/2}$. (This can give a correction even when the operator ξ_f preserves the polarization.)

The condition for the existence of a metaplectic structure is essentially the same as the condition for the existence of spinors on the manifold, namely, the vanishing of the Stiefel-Whitney class; i.e., $\mathcal{H}^2(M, \mathbb{Z}_2) = 0$. (The metaplectic group is the covering group for the symplectic group, and $\delta_{-1/2}$ can be constructed using spinor frames.) If we have $\mathcal{H}^2(M, \mathbb{Z}_2) = 0$, then there can be inequivalent $\delta_{-1/2}$ bundles, which are classified by $\mathcal{H}^1(M, \mathbb{Z}_2) = 0$, exactly as for spinors.

The metaplectic structure gives a more formal and better way to address the issue of defining the integration measure for the inner product of the true wave functions and of having to modify the definition of operators corresponding to f as in (65). We will not go into this in any more detail here. The point is that, overall, while geometric quantization is very beautiful, it must be admitted that defining operators which do not preserve the polarization and defining an integration measure on the space of polarized wave functions are somewhat awkward and cumbersome. We will be considering mostly the holomorphic polarization which avoids most of these issues.

⁵By the way, $\sigma_r(\bar{P}) = \overline{\sigma_r(P)}$.

5 Topological features of quantization

There are two aspects of the topological features of phase space which have an impact on the quantization. These are due to first and second cohomology of the phase space. We will briefly talk about them now.

5.1 The case of nontrivial $\mathcal{H}^1(M, \mathbb{R})$

Consider first the case of $\mathcal{H}^1(M, \mathbb{R}) \neq 0$, which means that M admits one-forms which are closed but not exact. Thus for a given symplectic two-form Ω , we can have different symplectic potentials \mathcal{A} and $\mathcal{A} + A$ which lead to the same Ω since A is closed, i.e., $dA = 0$. Now if A is exact, there is some globally defined function h on M such that $A = dh$. The function h is a canonical transformation and physical results will be unchanged. Thus an exact one-form is equivalent to $A = 0$ upon carrying out a canonical transformation. However, if A is closed but not exact, i.e., it is a nontrivial element of the cohomology $\mathcal{H}^1(M, \mathbb{R})$, then we cannot get rid of it by a canonical transformation. Locally we can still write $A = df$ for some f , but f will not be globally defined on M . Thus globally we cannot eliminate A .

Classical dynamics is defined by the equations of motion as in (25) which involves only Ω , not the symplectic potential \mathcal{A} . Thus this ambiguity in the choice of the symplectic potential due to nonzero $\mathcal{H}^1(M, \mathbb{R})$ will not affect the classical dynamics. In the quantum theory such A 's do make a difference. This can be seen in terms of the action \mathcal{S} ; for a path C , parametrized as $q^\mu(t)$ from a point a on M to a point b , the action is

$$\mathcal{S} = \int dt \left(\mathcal{A}_\mu \frac{dq^\mu}{dt} - H \right) + \int_a^b A_\mu dq^\mu \quad (69)$$

The action depends on the path but the contribution from A is topological. If we change the path slightly from C to C' with the end points fixed, we find, using Stokes' theorem,

$$\int_C A - \int_{C'} A = \oint_{C-C'} A = \int_\Sigma dA = 0 \quad (70)$$

where $C - C'$ is the path where we go from a to b along C and back from b to a along C' . (Since this is the return path, the orientation is reversed, hence the minus sign.) Σ is a surface in M with $C - C'$ as the boundary. The above result shows that the contribution from A is invariant under small changes of the path, which also explains why it does not contribute to the classical equations of motion viewed as variational equations. (The full action \mathcal{S} does depend on the path.) In particular, the value of the integral of A is zero for closed paths so long as they are

contractible; for then we can make a sequence of small deformations of the path (which do not change the value) and eventually contract the path to zero. If there are noncontractible loops then there can be nontrivial contributions. If $\mathcal{H}^1(M, \mathbb{R}) \neq 0$, then there are noncontractible loops. In the quantum theory, it is e^{iS} which is important, so we need $e^{i \int A}$. Assume for simplicity that $\mathcal{H}^1(M, \mathbb{R})$ has only one nontrivial element (say α) up to addition of trivial terms and multiplicative factors. Then there is only one topologically distinct noncontractible loop apart from multiple traversals of the same. Let $A = \theta \alpha$ where θ is a constant and α is normalized to unity along the noncontractible loop for going round once. For all paths which include n traversals of the loop, we find

$$\exp\left(i \oint A\right) = \exp\left(i \theta \oint \alpha\right) = \exp(i \theta n) \quad (71)$$

Notice that a shift $\theta \rightarrow \theta + 2\pi$ does not change this value, so that we may restrict θ to be in the interval zero to 2π . Putting this back into the action (70), we see that, as a function over all paths, the action has an extra parameter θ . Thus the ambiguity in the choice of the symplectic potential due to $\mathcal{H}^1(M, \mathbb{R}) \neq 0$ leads to an extra parameter θ which is needed to fully characterize the quantum theory. Since θ is in the interval 0 to 2π , we may regard $A = \theta \alpha$ as an element of $\mathcal{H}^1(M, \mathbb{R})/\mathcal{H}^1(M, \mathbb{Z})$. If $\mathcal{H}^1(M, \mathbb{R})$ has more than one distinct element, there are more distinct paths possible and there can be more parameters like θ . Such parameters are generally called vacuum angles.

It is now easy to see these results in terms of wave functions. The relevant covariant derivatives are of the form $\mathcal{D}_\mu \Psi = (\partial_\mu - i\mathcal{A}_\mu - iA_\mu)\Psi$. We can write

$$\Psi(q) = \exp\left(i \int_0^q A\right) \Phi(q) \quad (72)$$

where the lower limit of the integral is some fixed point a . By using this in the covariant derivative, we see that A is removed from \mathcal{D}_μ in terms of action on Φ . This is a like canonical transformation, except that the relevant transformation $\exp(i \int_0^q A)$ is not single valued. As we go around a closed noncontractible curve, it can give a phase $e^{i\theta}$. Since Ψ is single-valued, this means that Φ must have a compensating phase factor; Φ is not single-valued but must give a specific phase labelled by θ . Thus we can get rid of A from the covariant derivatives and hence the various operator formulae, but diagonalizing the Hamiltonian on such Φ 's can give results which depend on the angle θ .

The θ -vacua in a nonabelian gauge theory is an example of this kind of topological feature. The description of particles of fractional statistics in two spatial dimensions is another example.

5.2 The case of nontrivial $\mathcal{H}^2(M, \mathbb{R})$

We now turn to the second topological feature we mentioned, namely the case of $\mathcal{H}^2(M, \mathbb{R}) \neq 0$. This means that there are closed two-forms on M which are not exact. Correspondingly, there are closed two-surfaces which are not the boundaries of any three-dimensional region, i.e., there exists noncontractible closed two-surfaces. In general, elements of $\mathcal{H}^2(M, \mathbb{R})$ integrated over such noncontractible two-surfaces will not be zero. If the symplectic two-form Ω is some nontrivial element, or it has a part which is a nontrivial element, of $\mathcal{H}^2(M, \mathbb{R})$, then the symplectic potential \mathcal{A} cannot be globally defined. This can be seen as follows. Consider the integral of Ω over a noncontractible two-surface Σ ,

$$I(\Sigma) = \int_{\Sigma} \Omega \quad (73)$$

First of all, this is a topological invariant, for if Σ' is a small deformation of Σ , then

$$I(\Sigma) - I(\Sigma') = \int_{\Sigma - \Sigma'} \Omega = \int_V d\Omega = 0 \quad (74)$$

where V is a three-dimensional volume with the two surfaces $\Sigma - \Sigma'$ as the boundary. Thus the integral of Ω is invariant under small deformations of the surface on which it is integrated. If we could write Ω as $d\mathcal{A}$ for some \mathcal{A} which is globally defined on Σ then clearly $I(\Sigma)$ is zero by Stokes' theorem. Thus if $I(\Sigma)$ is nonzero, we must conclude that there is no potential \mathcal{A} which is globally defined on Σ . We have to use different choices for \mathcal{A} in different coordinate patches and have transition functions relating the \mathcal{A} 's in the overlap regions. But we have the same Ω on a given overlap region whether we use the \mathcal{A} for one patch or the \mathcal{A} for the other patch to calculate it. Thus the transition functions on overlap regions must be canonical transformations.

As an example, consider a closed noncontractible two-sphere, or any smooth deformation of it, which may be a subspace of M . We can cover it with two coordinate patches corresponding to the two hemispheres, denoted N and S as usual. The symplectic potential is represented by \mathcal{A}_N and \mathcal{A}_S respectively. On the equatorial overlap region, they are connected by

$$\mathcal{A}_N = \mathcal{A}_S + d\Lambda \quad (75)$$

where Λ is a function defined on the overlap region. It gives the canonical transformation between the two \mathcal{A} 's.

The symplectic potential \mathcal{A} is what is needed in setting up the quantum theory. And since canonical transformations are represented as unitary transformations on the wave functions, we see that we must also have a Ψ_N for the patch N and a Ψ_S for the patch S . On the equator

they must be related by the canonical transformation, which from (38), is given as

$$\Psi_N = \exp(i\Lambda) \Psi_S \quad (76)$$

Now consider the integral of $d\Lambda$ over the equator E , which is a closed curve being the boundary of either N or S . From (75) this is given as

$$\begin{aligned} \Delta\Lambda &= \oint_E d\Lambda = \int_E \mathcal{A}_N - \int_E \mathcal{A}_S = \int_{\partial N} \mathcal{A}_N + \int_{\partial S} \mathcal{A}_S \\ &= \int_N \Omega + \int_S \Omega = \int_\Sigma \Omega \end{aligned} \quad (77)$$

(In the second step, we reverse the sign for the S -term because E considered as the boundary of S has the opposite orientation compared to it being the boundary of N .) The above equation shows that the change of Λ as we go around the equator once, namely $\Delta\Lambda$, is nonzero if $I(\Sigma)$ is nonzero; Λ is not single-valued on the equator. But the wave function must be single-valued. From (76), we see that this can be achieved if $\exp(i\Delta\Lambda) = 1$ or if $\Delta\Lambda = 2\pi n$ for some integer n . Combining with (77), this can be stated as a topological quantization rule implied by the single-valuedness of wave functions in the quantum theory,

$$\int_\Sigma \Omega = 2\pi n \quad (78)$$

The integral of the symplectic two-form Ω on closed noncontractible two-surfaces must be quantized as 2π times an integer. (Or we may say that Ω must belong to an integral cohomology class of M .) We have given the argument for surfaces which are deformations of a two-sphere, but a similar argument can be made for general noncontractible two-surfaces. The result (78) is quite general.

The quintessential example of this kind of topological feature is the motion of a charged particle in the field of a magnetic monopole. The condition (78) is then the famous Dirac quantization condition. The Wess-Zumino terms occurring in many field theories are another example.

6 Summary of holomorphic polarization and quantization

Since we will be using geometric quantization with holomorphic polarization in some of the examples later, this is a good point to summarize the key features of quantization using the holomorphic polarization.

1. We need a phase space which is also Kähler; the symplectic two-form must be a multiple of the Kähler form.

2. The polarization condition is chosen as $\mathcal{D}_{\bar{a}} \Psi = 0$.
3. The inner product of the prequantum Hilbert space, which is essentially square integrability on the phase space with the Liouville measure of integration, is retained as the inner product on the true Hilbert space in the holomorphic polarization.
4. The operator corresponding to an observable $f(q)$ which preserves the chosen polarization is given by the prequantum operator $\mathcal{P}(f)$ acting on the true (polarized) wave functions.
5. For observables which do not preserve the polarization, one has to construct infinitesimal unitary transformations whose classical limits are the required canonical transformations.
6. If $\mathcal{H}^1(M, \mathbb{R})$ is not zero, then there are inequivalent \mathcal{A} 's for the same Ω and we need extra angular parameters to specify the quantum theory completely.
7. If the phase space M has noncontractible two-surfaces, then the integral of Ω over any of these surfaces must be quantized in units of 2π .

7 Coherent states, the two-sphere and G/H spaces

7.1 Coherent states

We will start with the simplest case of coherent states for a one-dimensional quantum system to illustrate how these ideas take concrete form. In one spatial dimension, $\Omega = dp \wedge dx = idz \wedge d\bar{z}$, where $(p \pm ix)/\sqrt{2} = z, \bar{z}$. Choose

$$\mathcal{A} = \frac{i}{2}(z d\bar{z} - \bar{z} dz) \quad (79)$$

The space is Kähler, with $K = \bar{z}z$. The covariant derivatives corresponding to (79) are $\partial_z - \frac{1}{2}\bar{z}$ and $\partial_{\bar{z}} + \frac{1}{2}z$. Holomorphic polarization corresponds to $P = \partial/\partial\bar{z}$, so that the polarization condition on the prequantum wave functions is

$$(\partial_{\bar{z}} + \frac{1}{2}z)\Psi = 0 \quad (80)$$

The solutions are of the form

$$\Psi = e^{-\frac{1}{2}z\bar{z}} \varphi(z) \quad (81)$$

where $\varphi(z)$ is holomorphic in z . The Hamiltonian vector fields corresponding to z, \bar{z} are

$$z \longleftrightarrow -i\frac{\partial}{\partial\bar{z}}, \quad \bar{z} \longleftrightarrow i\frac{\partial}{\partial z} \quad (82)$$

These commute with $P = \partial/\partial\bar{z}$ and so are polarization-preserving. The prequantum operators corresponding to these are

$$\begin{aligned}\mathcal{P}(z) &= -i(-i) \left(\frac{\partial}{\partial\bar{z}} + \frac{1}{2}z \right) + z = -\frac{\partial}{\partial\bar{z}} + \frac{1}{2}z \\ \mathcal{P}(\bar{z}) &= -i(i) \left(\frac{\partial}{\partial z} - \frac{1}{2}\bar{z} \right) + \bar{z} = \frac{\partial}{\partial z} + \frac{1}{2}\bar{z}\end{aligned}\quad (83)$$

In terms of their action on the functions $\varphi(z)$ in (81), corresponding to Ψ 's obeying the polarization condition, these can be written as

$$\begin{aligned}\mathcal{P}(z) \varphi(z) &= z \varphi(z) \\ \mathcal{P}(\bar{z}) \varphi(z) &= \frac{\partial\varphi}{\partial z}\end{aligned}\quad (84)$$

The inner product for the $\varphi(z)$'s is

$$\langle 1|2\rangle = \int i \frac{dz \wedge d\bar{z}}{2\pi} e^{-z\bar{z}} \varphi_1^* \varphi_2 \quad (85)$$

What we have obtained is the standard coherent state (or Bargman) realization of the Heisenberg algebra.

7.2 Quantizing the two-sphere

We now consider the example of the phase space being a two-sphere S^2 . This space can be considered as $\mathbb{C}\mathbb{P}^1$, the complex projective space in one (complex) dimension. It is a Kähler manifold. We may also regard S^2 as $SU(2)/U(1)$, a point of view which is useful for generalization later. We will consider quantization of the two-sphere first in local coordinates, then using homogeneous coordinates for $\mathbb{C}\mathbb{P}^1$, and then from the group theory point of view.

Quantization using local coordinates

We introduce local complex coordinates for $\mathbb{C}\mathbb{P}^1$ as $z = x + iy$, $\bar{z} = x - iy$, the standard Kähler two-form is given by

$$\omega = i \frac{dz \wedge d\bar{z}}{(1 + z\bar{z})^2} \quad (86)$$

These coordinates can be related to an embedding of S^2 in \mathbb{R}^3 via

$$X_1 = \frac{z + \bar{z}}{(1 + z\bar{z})}, \quad X_2 = \frac{i(z - \bar{z})}{(1 + z\bar{z})}, \quad X_3 = \frac{1 - z\bar{z}}{(1 + z\bar{z})} \quad (87)$$

so that we may view z, \bar{z} as the coordinates of a plane onto which the sphere is stereographically projected. The metric is given by $ds^2 = e^1 e^1 + e^2 e^2$ where the frame fields are

$$e^1 = \frac{dx}{1 + r^2}, \quad e^2 = \frac{dy}{1 + r^2} \quad (88)$$

The Riemannian curvature is $R_2^1 = 4 e^1 \wedge e^2$ giving the Euler number

$$\chi = \int \frac{R_{12}}{2\pi} = 2 \quad (89)$$

The phase space has nonzero $\mathcal{H}^2(M, \mathbb{R})$ with its generating element given by the Kähler two-form, which is also proportional to the volume form for S^2 . As the discussion which led to (78) showed, the symplectic two-form must belong to an integral cohomology class of M to be able to quantize properly. So we consider the symplectic form

$$\Omega = n \omega = i n \frac{dz \wedge d\bar{z}}{(1 + z\bar{z})^2} = i \partial \bar{\partial} K, \quad K = n \log(1 + z\bar{z}) \quad (90)$$

where n is an integer; In this case, $\int_M \Omega = 2\pi n$ as required by the quantization condition. K is the Kähler potential for Ω . Classically the Poisson bracket of two functions F and G on the phase space is given by

$$\begin{aligned} \{F, G\} &= \Omega^{\mu\nu} \partial_\mu F \partial_\nu G \\ &= \frac{i}{n} (1 + z\bar{z})^2 \left(\frac{\partial F}{\partial z} \frac{\partial G}{\partial \bar{z}} - \frac{\partial F}{\partial \bar{z}} \frac{\partial G}{\partial z} \right) \end{aligned} \quad (91)$$

Turning to the quantization, first of all, the symplectic potential corresponding to the Ω in (90) can be taken as

$$\mathcal{A} = \frac{in}{2} \left[\frac{z d\bar{z} - \bar{z} dz}{(1 + z\bar{z})} \right] \quad (92)$$

The covariant derivatives are given by $\partial - i\mathcal{A}$. The holomorphic polarization condition is

$$(\partial_{\bar{z}} - i\mathcal{A}_{\bar{z}})\Psi = \left[\partial_{\bar{z}} + \frac{n}{2} \frac{z}{(1 + z\bar{z})} \right] \Psi = 0 \quad (93)$$

This can be solved as

$$\Psi = \exp\left(-\frac{n}{2} \log(1 + z\bar{z})\right) f(z) \quad (94)$$

Notice that we have a factor $\exp(-\frac{1}{2}K)$ as expected. The inner product is given by

$$\langle 1|2\rangle = ic \int \frac{dz \wedge d\bar{z}}{2\pi(1 + z\bar{z})^{n+2}} f_1^* f_2 \quad (95)$$

Here c is an overall constant, which can be absorbed into the normalization factors for the wave functions. Since $f(z)$ in (94) is holomorphic, we can see that a basis of nonsingular wave functions is given by $f(z) = 1, z, z^2, \dots, z^n$; higher powers of z will not have finite norm. The dimension of the Hilbert space is thus $(n + 1)$. We could have seen that this dimension would be finite from the semiclassical estimate of the number of states as the phase volume. Since the phase volume is finite for $M = S^2$, the dimension of the Hilbert space should be finite.

It is interesting to see this dimension in another way. The polarization condition (93) is giving the $\bar{\partial}$ -closure of Ψ with a $U(1)$ gauge field \mathcal{A} and on a space of Riemannian curvature R_{12} . The number of normalizable solutions to (93) is thus given by the index theorem for the twisted Dolbeault complex, i.e.,

$$\text{index}(\bar{\partial}_V) = \int_M \text{td}(M) \wedge \text{ch}(V) \quad (96)$$

where, for our two-dimensional case, the Todd class $\text{td}(M)$ is $R/4\pi$ and the Chern character $\text{ch}(V) = \text{Tr}(e^{F/2\pi})$ is $\int \Omega/2\pi$ for us [6]. We thus have

$$\text{index}(\bar{\partial}_V) = \int_M \frac{\Omega}{2\pi} + \int_M \frac{R}{4\pi} = n + 1 \quad (97)$$

Notice that, semiclassically, we should expect the number of states to be $\int \Omega/2\pi = n$. The extra one comes from the Euler number in this case. (The semiclassical counting is supposed to apply only for large n , so this is all consistent with expectations.)

An orthonormal basis for the wave functions may be taken to be

$$f_k(z) = \left[\frac{n!}{k!(n-k)!} \right]^{\frac{1}{2}} z^k \quad (98)$$

with the inner product

$$\langle 1|2\rangle = i(n+1) \int \frac{dz \wedge d\bar{z}}{2\pi(1+z\bar{z})^{n+2}} f_1^* f_2 \quad (99)$$

Here we have chosen the parameter c in (95) such that the trace of the identity operator is $n+1$.

Consider now the vector fields

$$\xi_+ = i \left(\frac{\partial}{\partial \bar{z}} + z^2 \frac{\partial}{\partial z} \right), \quad \xi_- = i \left(\frac{\partial}{\partial z} + \bar{z}^2 \frac{\partial}{\partial \bar{z}} \right), \quad \xi_3 = i \left(z \frac{\partial}{\partial z} - \bar{z} \frac{\partial}{\partial \bar{z}} \right) \quad (100)$$

It is easily verified that these are the standard $SU(2)$ isometries of the sphere. The Lie commutator of the ξ 's give the $SU(2)$ algebra. Further, these are Hamiltonian vector fields corresponding to the functions

$$J_+ = -n \frac{z}{1+z\bar{z}}, \quad J_- = -n \frac{\bar{z}}{1+z\bar{z}}, \quad J_3 = -\frac{n}{2} \left(\frac{1-z\bar{z}}{1+z\bar{z}} \right) \quad (101)$$

The prequantum operators $-i\xi \cdot \mathcal{D} + J$ corresponding to these functions are

$$\begin{aligned} \mathcal{P}(J_+) &= (z^2 \partial_z - nz) - i\xi_+^{\bar{z}} \mathcal{D}_{\bar{z}} \\ \mathcal{P}(J_-) &= \left(-\partial_z - \frac{n}{2} \frac{\bar{z}}{1+z\bar{z}} \right) - i\xi_-^{\bar{z}} \mathcal{D}_{\bar{z}} \\ \mathcal{P}(J_3) &= \left(z \partial_z - \frac{n}{2} \frac{1}{1+z\bar{z}} \right) - i\xi_3^{\bar{z}} \mathcal{D}_{\bar{z}} \end{aligned} \quad (102)$$

Acting on the polarized wave functions, \mathcal{D}_z in these expressions will give zero. Writing Ψ as in (94), we can work out the action of the operators on the holomorphic wave functions $f(z)$, by moving the derivatives through the $e^{-\frac{1}{2}K}$ factor. We then find

$$\begin{aligned}\hat{J}_+ f &= (z^2 \partial_z - n z) f \\ \hat{J}_- f &= (-\partial_z) f \\ \hat{J}_3 f &= (z \partial_z - \frac{1}{2} n) f\end{aligned}\tag{103}$$

If we define $j = n/2$, which is therefore half-integral, we see that the operators given above correspond to a unitary irreducible representation of $SU(2)$ with $J^2 = j(j+1)$ and dimension $n+1 = 2j+1$. Notice that there is only one representation here and it is fixed by the choice of the symplectic form Ω . In other words, the quantization of the two-sphere with the symplectic form (90) gives one unitary irreducible representation of $SU(2)$ with $j = n/2$.

Quantization using homogeneous coordinates

The complex coordinates we used are only local coordinates valid in a coordinate patch around $z = 0$; strictly speaking we need at least another coordinate patch with a different choice of coordinates to describe the sphere in a nonsingular way. This would be valid around $z = \infty$; it did not matter too much in what we did, because the potential coordinate singularity is basically a point with zero measure.

A more global approach is to use the homogeneous coordinates of the sphere viewed as $\mathbb{C}P^1$. Recall that the complex projective space $\mathbb{C}P^k$ is defined by $(k+1)$ complex coordinates $(u_1, u_2, \dots, u_{k+1}) \in \mathbb{C}^{k+1}$ with the identification $(u_1, u_2, \dots, u_{k+1}) \sim \lambda(u_1, u_2, \dots, u_{k+1})$, for any complex nonzero λ , $\lambda \in \mathbb{C} - \{0\}$. Thus, for $\mathbb{C}P^1$, we will need two u 's which we may think of as a two-component spinor u_α , $\alpha = 1, 2$, with the identification $u_\alpha \sim \lambda u_\alpha$. We also define $\bar{u}_1 = u_2^*$, $\bar{u}_2 = -u_1^*$ or $\bar{u}_\alpha = \epsilon_{\alpha\beta} u_\beta^*$, where $\epsilon_{\alpha\beta} = -\epsilon_{\beta\alpha}$, $\epsilon_{12} = 1$. The symplectic form is

$$\Omega = -i n \left[\frac{du \cdot d\bar{u}}{\bar{u} \cdot u} - \frac{\bar{u} \cdot du \cdot u \cdot d\bar{u}}{(\bar{u} \cdot u)^2} \right]\tag{104}$$

where the notation is $u \cdot v = u_\alpha v_\beta \epsilon_{\alpha\beta}$. This means that $\bar{u} \cdot v = u^\dagger v = u_1^* v_1 + u_2^* v_2$. It is easily checked that $\Omega(\lambda u) = \Omega(u)$; it is invariant under $u \rightarrow \lambda u$ and hence is properly defined on $\mathbb{C}P^1$ rather than \mathbb{C}^2 . The choice of $u_2/u_1 = z$ leads to the previous local parametrization; this is valid around $u_1 \neq 0$. We can use another coordinate patch with the local coordinates $w = u_1/u_2$. These two patches will correspond to the north and south hemispheres of the sphere, in a stereographic projection.

The symplectic potential corresponding to (104) is

$$\mathcal{A} = -i\frac{n}{2} \left[\frac{u \cdot d\bar{u} - du \cdot \bar{u}}{\bar{u} \cdot u} \right] \quad (105)$$

Directly from the above expression we see that

$$\mathcal{A}(\lambda u) = \mathcal{A}(u) + d \left(i\frac{n}{2} \log(\bar{\lambda}/\lambda) \right) \quad (106)$$

This means that \mathcal{A} cannot be written as a globally defined form on \mathbb{CP}^1 since it is not invariant under the needed identification $u_\alpha \sim \lambda u_\alpha$. This is to be expected because $\int \Omega \neq 0$ and hence we cannot have a globally defined potential on \mathbb{CP}^1 . From the transformation law (106) and (38), we see that the prequantum wave functions must transform as

$$\Psi(\lambda u, \bar{\lambda} \bar{u}) = \Psi(u, \bar{u}) \exp \left[\frac{n}{2} \log(\lambda/\bar{\lambda}) \right] \quad (107)$$

The polarization condition for the wave functions becomes

$$\left[\frac{\partial}{\partial \bar{u}_\alpha} - \frac{n}{2} \frac{u_\beta \epsilon_{\beta\alpha}}{\bar{u} \cdot u} \right] \Psi = 0 \quad (108)$$

The solution to this condition is

$$\Psi = \exp \left(-\frac{n}{2} \log(\bar{u} \cdot u) \right) f(u) \quad (109)$$

Combining this with (107), we see that the holomorphic functions $f(u)$ should behave as

$$f(\lambda u) = \lambda^n f(u) \quad (110)$$

$f(u)$ must thus have n u 's and hence is of the form

$$f(u) = \sum_{\alpha's} C^{\alpha_1 \dots \alpha_n} u_{\alpha_1} \dots u_{\alpha_n} \quad (111)$$

Because of the symmetry of the indices, there are $n + 1$ independent functions, as before. There is a natural linear action of $SU(2)$ on the u, \bar{u} given by

$$u'_\alpha = U_{\alpha\beta} u_\beta, \quad \bar{u}'_\alpha = U_{\alpha\beta} \bar{u}_\beta \quad (112)$$

where $U_{\alpha\beta}$ form a (2×2) $SU(2)$ matrix. The corresponding generators are the J_a we have constructed in (102, 103). We have thus recovered all the previous results in a more global way.

Group theoretic version

Equation (28) relating the action and the symplectic potential \mathcal{A} shows that the potential of interest to us, namely, (92) can be obtained from the action

$$\mathcal{S} = i\frac{n}{2} \int dt \frac{z\dot{\bar{z}} - \bar{z}\dot{z}}{1 + z\bar{z}} \quad (113)$$

where the overdot denotes differentiation with respect to time. This action may be written as

$$\mathcal{S} = i\frac{n}{2} \int dt \operatorname{Tr}(\sigma_3 g^{-1} \dot{g}) \quad (114)$$

where g is an element of $SU(2)$ written as a (2×2) -matrix, $g = \exp(i(\sigma_i/2)\theta_i)$ and $\sigma_i, i = 1, 2, 3$, are the Pauli matrices. In this action, the dynamical variable is thus an element of $SU(2)$. There are many ways to parametrize the group element, corresponding to local coordinates on the group viewed as a Riemannian manifold. One convenient parametrization is given by

$$g = \frac{1}{\sqrt{1+z\bar{z}}} \begin{pmatrix} 1 & z \\ -\bar{z} & 1 \end{pmatrix} \begin{bmatrix} e^{i\theta} & 0 \\ 0 & e^{-i\theta} \end{bmatrix} \quad (115)$$

If this is used in (114), we get (113).

In the action (114), if we make a transformation $g \rightarrow g h$, $h = \exp(i\sigma_3\varphi)$, we get

$$\mathcal{S} \rightarrow \mathcal{S} - n \int dt \dot{\varphi} \quad (116)$$

The extra term is a boundary term and does not affect the equations of motion. (It is for this same reason that θ in (115) does not appear in (113).) Since equations of motion do not depend on θ , we see that classically the dynamics is actually restricted to $SU(2)/U(1) = S^2$.

Even though the classical dynamics is restricted to $SU(2)/U(1)$, the boundary term in (116) does have an effect in the quantum theory. Consider choosing $\varphi(t)$ such that $\varphi(-\infty) = 0$ and $\varphi(\infty) = 2\pi$. In this case $h(-\infty) = h(\infty) = 1$ giving a closed loop in the $U(1)$ subgroup of $SU(2)$ defined by the σ_3 -direction. For this choice of $h(t)$, the action changes by $-2\pi n$. $e^{i\mathcal{S}}$ remains single-valued and, even in the quantum theory, the extra $U(1)$ degree of freedom is consistently removed. If the coefficient were not an integer, this would not be the case and we would have inconsistencies in the quantum theory. The quantization of the coefficient to an integral value is seen again from a slightly different point of view.

We can now move ahead and complete the quantization. The canonical one-form is obtained from \mathcal{S} as

$$\mathcal{A} = i\frac{n}{2} \operatorname{Tr}(\sigma_3 g^{-1} dg) \quad (117)$$

The prequantum wave functions are sections of a bundle on $SU(2)/U(1)$. Let us start with functions on $SU(2)$. A function on $SU(2)$ may be written as a linear combination of the representation matrices $\mathcal{D}_{ab}^{(j)}(g)$ as

$$\Psi = \sum_j \sum_{a,b} C_{ab}^{(j)} \mathcal{D}_{ab}^{(j)}(g) = \sum_j \sum_{a,b} C_{ab}^{(j)} \langle a | e^{i\hat{J}_i \theta_i} | b \rangle \quad (118)$$

where \hat{J}_i is the angular momentum or $SU(2)$ generator in an arbitrary representation. (The matrices $\mathcal{D}_{ab}^{(j)}(g)$ are also known as the Wigner \mathcal{D} -functions.) Consider the transformation $g \rightarrow gh$, $h = \exp(-i\frac{\sigma_3}{2}\theta)$; the change in \mathcal{A} is given by $\mathcal{A} \rightarrow \mathcal{A} + (n/2)d\theta$. Since $\sigma_3/2$ corresponds to \hat{J}_3 in an arbitrary representation, this implies that the wave functions must obey

$$\Psi\left(g e^{-i\hat{J}_3\theta}\right) = \Psi(g) \exp\left(\frac{in}{2}\theta\right) \quad (119)$$

This identifies the J_3 -eigenvalue of the state corresponding to b in (118) as $-n/2$, so that $|b\rangle = |j, -\frac{n}{2}\rangle$.

We have considered translations of g on the right by $h \in U(1)$. The remaining generators for the right action are $R_{\pm} = R_1 \pm iR_2$, where R_i is defined by

$$R_i g = g \frac{\sigma_a}{2} \quad (120)$$

The combinations R_{\pm} are complex and conjugate to each other. We can take R_- as the polarization condition, requiring the wave functions to obey

$$R_- \Psi = R_- \sum_j \sum_{a,b} C_{ab}^{(j)} \langle a | e^{i\hat{J}_i\theta_i} | b \rangle = \sum_j \sum_{a,b} C_{ab}^{(j)} \langle a | e^{i\hat{J}_i\theta_i} \hat{J}_- | b \rangle = 0 \quad (121)$$

This is a holomorphicity condition and upon using the parametrization (115) will be seen to be identical to the condition (93), namely, $\mathcal{D}_{\bar{z}}\Psi = 0$. From the group theory point of view, (121) means that the state $|b\rangle$ must also be the lowest weight state. A lowest weight state with $J_3 = -n/2$ means that $j = n/2$. Thus only one representation in (118) will have nonzero coefficients, identifying the general wave function as

$$\Psi = \sum_a C_{a,-\frac{n}{2}}^{(\frac{n}{2})} \mathcal{D}_{a,-\frac{n}{2}}^{(\frac{n}{2})}(g) \quad (122)$$

A general state is a linear combination of $\mathcal{D}_{a,-\frac{n}{2}}^{(\frac{n}{2})}(g)$; since a takes $2j + 1$ values, we see that the Hilbert space corresponds to a unitary irreducible representation of $SU(2)$ with $j = n/2$. The operators J_i given in (102) or (103) correspond to the left action on g , i.e.,

$$J_i \Psi(g) = \sum_a C_{a,-\frac{n}{2}}^{(\frac{n}{2})} \mathcal{D}_{a,-\frac{n}{2}}^{(\frac{n}{2})}\left(\frac{\sigma_i}{2}g\right) = \sum_{a,c} C_{a,-\frac{n}{2}}^{(\frac{n}{2})} (J_i)_{ac} \mathcal{D}_{c,-\frac{n}{2}}^{(\frac{n}{2})}(g) \quad (123)$$

Here $(J_i)_{ac}$ is the matrix version of \hat{J}_i in the representation with $j = n/2$. We have thus reproduced the previous results from a purely group theoretic point of view.

Before we consider the generalization of this to arbitrary groups, it is useful to mention some examples where these results turn up. We may regard the $\Omega = n\omega$ as a $U(1)$ magnetic field which

is constant (in the appropriate coordinates) on the sphere. This point of view is further supported by looking at R_{\pm} . These are translation operators on the sphere, but their commutator is given by $[R_+, R_-] \Psi = 2 R_3 \Psi = n \Psi$. The commutator of derivatives is the gauge field, so we can identify a magnetic field for this case as $2B = n$. (We set the electric charge to be 1; also we took the sphere to have radius equal to 1, otherwise this would read $2BR^2 = n$ where R is the radius.) The quantization of the magnetic flux is the Dirac quantization condition again. Thus the states (122) we find are the angular part of the wave functions for a charged particle in the presence of a magnetic monopole [7]. Also they can be thought of as the lowest Landau levels for a constant magnetic field on the sphere [8, 9]. The left action of the J_i as in (123) correspond to the so-called magnetic translations for the Landau levels. So quantum Hall effect on the sphere can be discussed using these wave functions.

This can also appear as part of the dynamics of a particle with spin; we get one UIR of $SU(2)$, so we have exactly what is needed for spin. It can also be thought of as describing the internal symmetry structures, such as the color degrees of freedom for a particle with nonabelian charges for the case of the color group being $SU(2)$.

7.3 Kähler spaces of the G/H -type

The two-sphere $S^2 = SU(2)/U(1)$ is an example of a group coset which is a Kähler manifold. There are many Kähler manifolds which are of the form G/H where H is a subgroup of a compact Lie group G . In particular G/H is a Kähler manifold for any compact Lie group if H is its maximal torus. Another set of Kähler spaces of this type is given by $\mathbb{C}\mathbb{P}^k = SU(k+1)/U(k)$. There are also examples of this type corresponding to noncompact groups. For example, the Lobachevskian space $SL(2, \mathbb{R})/U(1)$ is also a Kähler manifold, although its volume defined by the Kähler two-form is infinite. There are many other cases as well [10].

In these cases, one can consider theories where the symplectic form is proportional to the Kähler form or is a combination of the generators of $\mathcal{H}^2(M, \mathbb{R})$ for these manifolds and quantize as we have done for the case of S^2 . The general result is that they lead to one unitary irreducible representation (UIR) of the group G , the specific representation being determined by the choice of Ω .

Quantizing $\mathbb{C}\mathbb{P}^2$

In most of these cases with G/H structure, it is rather simple and straightforward to construct the Kähler form for these spaces. We will consider in some detail another example, namely, the quantization of $\mathbb{C}\mathbb{P}^2 = SU(3)/U(2)$. A general element of $SU(3)$ can be represented

as a unitary (3×3) -matrix. This is of the form $g = \exp(it_a \theta^a)$, where the generators $\{t_a\}$ in the 3×3 matrix representation can be chosen as

$$\begin{aligned}
t_1 &= \frac{1}{2} \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} & t_2 &= \frac{1}{2} \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} & t_3 &= \frac{1}{2} \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix} & t_4 &= \frac{1}{2} \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \\
t_5 &= \frac{1}{2} \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix} & t_6 &= \frac{1}{2} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} & t_7 &= \frac{1}{2} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix} & t_8 &= \frac{1}{\sqrt{12}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}
\end{aligned} \tag{124}$$

(Our t_a are normalized so that $\text{Tr}(t_a t_b) = \frac{1}{2} \delta_{ab}$.) We define a $U(1)$ subgroup by elements of the form $U = \exp(it_8 \theta^8)$ and we can also define an $SU(2)$ subgroup which commutes with this $U(1)$ subgroup; the latter has elements of the form $U = \exp(it_a \theta^a)$ for $a = 1, 2, 3$. These two subgroups together form the $U(2)$ subgroup of $SU(3)$.⁶ Consider now the one-form

$$\mathcal{A}(g) = i w \text{Tr}(t_8 g^{-1} dg) = -i w \frac{\sqrt{3}}{2} u_\alpha du_\alpha^* \tag{126}$$

where g is an element of the group $SU(3)$ and w is a numerical constant; $u_\alpha^* = g_{\alpha 3}$. If h is an element of $U(2) \subset SU(3)$ of the form $h = U \exp(it_8 \theta)$, we find

$$\mathcal{A}(gh) = \mathcal{A}(g) - \frac{w}{2} d\theta \tag{127}$$

We see that \mathcal{A} changes by a total differential under the $U(2)$ -transformations. The two-form $d\mathcal{A}$ is therefore independent of θ or it is invariant under $U(2)$ transformations; it is a two-form defined on the coset space $SU(3)/U(2)$. Evidently it is closed ($d d\mathcal{A} = 0$ since $d^2 = 0$), but it is not exact since the corresponding one-form is not globally defined on $SU(3)/U(2)$, but only on $G = SU(3)$. Thus $d\mathcal{A}$ is a nontrivial element of $\mathcal{H}^2(SU(3)/U(2), \mathbb{R}) = \mathcal{H}^2(\mathbb{C}P^2, \mathbb{R})$. There will be quantization conditions on w and the lowest possible choice, with our choice of normalization for t_8 , will be $2/\sqrt{3}$. The Kähler 2-form for $SU(3)/U(2)$ is

$$\omega = d \left(i \frac{2}{\sqrt{3}} \text{Tr}(t_8 g^{-1} dg) \right) \tag{128}$$

⁶Strictly speaking there is an identification of certain elements involved. There is a common \mathbb{Z}_2 subgroup for the factors in $SU(2) \times U(1)$ defined by $\mathbb{Z}_2 = (1, h_Z)$, $h_Z = (h_2, h_1)$ with $h_Z^2 = 1$ and

$$h_2 = \begin{pmatrix} -1_{2 \times 2} & 0 \\ 0 & 1 \end{pmatrix}, \quad h_1 = \exp(it_8 \sqrt{12} \pi) = \begin{pmatrix} -1_{2 \times 2} & 0 \\ 0 & 1 \end{pmatrix} \tag{125}$$

The $U(2)$ subgroup is given by $SU(2) \times U(1)/\mathbb{Z}_2$.

The connection with the complex projective space is clarified by introducing $Z_\alpha = \rho u_\alpha$, where ρ is an arbitrary complex number, not equal to zero. We can then consider

$$\mathcal{A} = -i w \frac{\sqrt{3}}{2} \frac{Z \cdot d\bar{Z}}{\bar{Z} \cdot Z} = -i w \frac{\sqrt{3}}{2} [u_\alpha du_\alpha^* + d \log \rho] \quad (129)$$

This \mathcal{A} differs from (126) by a total derivative and hence $d\mathcal{A}$ will be the same for both \mathcal{A} 's. We thus see that we can write ω as

$$\omega = -i \left[\frac{dZ \cdot d\bar{Z}}{(Z \cdot \bar{Z})} - \frac{dZ \cdot \bar{Z} Z \cdot d\bar{Z}}{(Z \cdot \bar{Z})^2} \right] \quad (130)$$

which is the expected Kähler form on $\mathbb{C}\mathbb{P}^2$.

As the symplectic form for quantization, we can consider any integral multiple of ω ; we need an integral multiple, since the integrals of $\Omega = d\mathcal{A}$ over nontrivial two-cycles on $\mathbb{C}\mathbb{P}^2$ will have to be integers. Thus the possible choices for w are of the form $w = 2n/\sqrt{3}$, $n \in \mathbb{Z}$.⁷ Therefore we will consider the symplectic two-form

$$\begin{aligned} \Omega &= -i \frac{2n}{\sqrt{3}} \text{Tr} (t_8 g^{-1} dg \wedge g^{-1} dg) \\ &= n\omega = -i n \left[\frac{dZ \cdot d\bar{Z}}{(Z \cdot \bar{Z})} - \frac{dZ \cdot \bar{Z} Z \cdot d\bar{Z}}{(Z \cdot \bar{Z})^2} \right] \end{aligned} \quad (131)$$

The action which leads to the chosen \mathcal{A} and the Ω in (131) is

$$\mathcal{S} = i \frac{2n}{\sqrt{3}} \int dt \text{Tr} (t_8 g^{-1} \dot{g}) \quad (132)$$

Again, for $e^{i\mathcal{S}}$ to be well defined on $\mathbb{C}\mathbb{P}^2$, the values of w will have to be restricted to the form given above, namely, $w = 2n/\sqrt{3}$, $n \in \mathbb{Z}$. The wave functions are functions on $SU(3)$ subject to the restrictions given by the action of $SU(2)$ and $U(1)$ and a holomorphicity condition. In other words, we can write, using the Wigner \mathcal{D} -functions for $SU(3)$

$$\Psi \sim \mathcal{D}_{AB}^{(r)}(g) = \langle r, A | \hat{g} | r, B \rangle \quad (133)$$

Here (r) is a set of indices which labels the representation, A, B label the states within a representation. Only the finite-dimensional (and hence unitary) representations can occur here, since they form a complete set for functions on $SU(3)$.

The groups involved in the quotient can be taken as the right action on g . The transformation law for \mathcal{A} then tells us that Ψ must transform as

$$\Psi(g h) = \Psi(g) \exp \left(-i \frac{n}{\sqrt{3}} \theta \right) \quad (134)$$

⁷It should be kept in mind that different choices of w correspond to different theories and different physics.

This shows that the wave functions must be singlets under the $SU(2)$ subgroup and carry a definite charge $n/\sqrt{3}$ under the $U(1)$ subgroup generated by t_8 . This restricts the choice of values for the state $|r, B\rangle$ in (133). Further $w = 2n/\sqrt{3}$ must also be quantized so that it can be one of the allowed values in the representations of $SU(3)$ in (133). This is the same as what we already found, namely, that n must be an integer.

One has to choose a polarization condition as well. The generators of $SU(3)$ can be divided into those of the $SU(2)$ and $U(1)$ subgroups, and the coset ones which correspond to t_i with $i = 4, 5, 6, 7$. These can be grouped into $t_a, t_{\bar{a}}$ and corresponding to $= t_4 + it_5, t_6 + it_7$ and their conjugates, $a, \bar{a} = 1, 2$. Correspondingly, we can define the right translation operators

$$R_a g = g t_a, \quad R_{\bar{a}} g = g t_{\bar{a}} \quad (135)$$

As the holomorphic polarization condition, we choose

$$R_{\bar{a}} \Psi(g) = 0 \quad (136)$$

This requires the state $|r, B\rangle$ to be a highest weight state. This requirement, along with the earlier statement that $|r, B\rangle$ should be an $SU(2)$ singlet with eigenvalue $n/\sqrt{3}$ for t_8 transformation, completely fixes the representation r and the state $|r, B\rangle$. The left index A is, however, free, running over the possible states in the representation r . Thus the result of the quantization is to yield a Hilbert space which is one unitary irreducible representation (UIR) of the group $SU(3)$.

Quantizing general G/H spaces

More generally, with a view of obtaining UIRs of a compact Lie group G , one can take

$$\mathcal{A}(g) = i \sum_a w_a \text{Tr}(t_a g^{-1} dg) \quad (137)$$

where t_a are diagonal elements of the Lie algebra of G and w_a are a set of numbers. H will be the subgroup commuting with $\sum_a w_a t^a$; if w_a are such that all the diagonal elements of $\sum_a w_a t^a$ are distinct, then H will be the maximal torus of G . \mathcal{A} will change by a total differential under $g \rightarrow gh, h \in H$ and $d\mathcal{A}$ will be a closed nonexact form on G/H . If some of the eigenvalues of $\sum_a w_a t^a$ are equal, H can be larger than the maximal torus. Upon quantization, for suitably chosen w_a , we will get one unitary irreducible representation of G and w_a will be related to the highest weights defining the representation [10].

There is another way to think about this problem. Let us say that we want to construct a UIR of a group G . We ask the question: Is there a classical action which upon quantization gives exactly one UIR of the group G ? Recall that if we quantize the rigid rotor we get all UIR's

of the angular momentum group $SO(3)$. That is not what we want, we want one and only one representation. The answer to this is the action

$$\mathcal{S} = i \sum_a w_a \int dt \operatorname{Tr}(t_a g^{-1} \dot{g}) \quad (138)$$

with the choice of $\{w_a\}$ determined by which representation we wish to obtain upon quantization.

One can use an action similar to (138) for noncompact groups as well. The key here is that, since we are quantizing the system, the representation we obtain is unitary. Thus if one carries out the quantization of $SL(2, \mathbb{R})/U(1)$, we will get a UIR of $SL(2, \mathbb{R})$. Such representations are infinite dimensional since $SL(2, \mathbb{R})$ is noncompact. The representation obtained will be one of the series needed for the completeness relation for functions on $SL(2, \mathbb{R})$. The infinite dimensionality is also in agreement with the semiclassical counting of the dimension of the Hilbert space since the phase volume (= the volume of $SL(2, \mathbb{R})/U(1)$ as measured by its Kähler form) is infinite.

A short historical note

Historically, geometric quantization arose out of representation theory for groups. The construction of UIR's of a compact group using the Kähler two-form on G/T where T is the maximal torus was carried out in the 1950s. It goes by the name of Borel-Weil-Bott theory. Geometric quantization was developed in the 1970s (by Kostant, Souriau, Kirillov and others) as an attempt to generalize this to arbitrary symplectic manifolds. The use of actions of the form (138) for various physical problems was pursued in the 1970s by Balachandran and others. This action (138) may also be viewed as the prototypical Wess-Zumino term. The usual Wess-Zumino term was introduced in the context of meson physics by Wess and Zumino in 1971 as an effective action for anomalies [11]. It was developed and its full import was realized in the work of Witten [12]. (In this context, Novikov's work on the Wess-Zumino term in a (2+1)-dimensional setting should be mentioned, although the physics implications were not fully evident [13]. There were also a few other earlier papers which focused on certain aspects of the Wess-Zumino term.)

8 The Chern-Simons theory in 2+1 dimensions

The Chern-Simons (CS) theory is a gauge theory in two space (and one time) dimensions [14]. The action is given by

$$\mathcal{S} = -\frac{k}{4\pi} \int_{\Sigma \times [t_i, t_f]} \operatorname{Tr} \left[A \wedge dA + \frac{2}{3} A \wedge A \wedge A \right]$$

$$= -\frac{k}{4\pi} \int_{\Sigma \times [t_i, t_f]} d^3x \epsilon^{\mu\nu\alpha} \text{Tr} \left[A_\mu \partial_\nu A_\alpha + \frac{2}{3} A_\mu A_\nu A_\alpha \right] \quad (139)$$

Here A_μ is the Lie algebra valued gauge potential, $A_\mu = -i t_a A_\mu^a$, corresponding to a compact Lie group G . t_a are hermitian matrices forming a basis of the Lie algebra in the fundamental representation of the gauge group. We shall the gauge group to be $G = SU(N)$ in what follows and normalize the t^a as $\text{Tr}(t_a t_b) = \frac{1}{2} \delta_{ab}$. Thus, for example, for the case of the gauge group being $SU(3)$, the set of matrices t_a can be taken as the ones given in (124). In addition to the choice of the group, the theory has one parameter k , which is a real constant whose precise value we do not need to specify at this stage. We shall consider the spatial manifold to be some Riemann surface Σ and we shall be using complex coordinates [14, 15]. The classical equations of motion for the theory are

$$F_{\mu\nu} = 0 \quad (140)$$

We shall now consider the quantization of the theory in the formalism we have developed. For this purpose, the theory is best analyzed in the gauge where A_0 is set to zero. In the $A_0 = 0$ gauge, the action becomes

$$\mathcal{S} = -\frac{ik}{\pi} \int dt d\mu_\Sigma \text{Tr}(A_{\bar{z}} \partial_0 A_z) \quad (141)$$

Taking the variation of the action, we see that the boundary term which results from the time-integration is

$$\delta\mathcal{S} = -\frac{ik}{\pi} \int_\Sigma \text{Tr}(A_{\bar{z}} \delta A_z) \Big]_{t_i}^{t_f} \quad (142)$$

As in (30), this identifies the symplectic potential as

$$\mathcal{A} = -\frac{ik}{\pi} \int_\Sigma \text{Tr}(A_{\bar{z}} \delta A_z) + \delta\rho[A] \quad (143)$$

where $\rho[A]$ is an arbitrary functional of A . The freedom of adding $\delta\rho$ is the freedom of canonical transformations. We have written A as a one-form on space; we also need one-forms on the space of the fields A ; to avoid confusion, we use δ to denote exterior derivatives on the space of fields. We may define the space of fields as follows. The potential A_i is a map from Σ to Lie algebra valued one-forms on Σ .

$$\mathfrak{F} = \{\text{Set of all gauge potentials } A_i\} \quad (144)$$

This is not the true space of physical field configurations, since potentials which differ by a gauge transformation are physically equivalent. We define

$$\mathfrak{G}_* = \{\text{Set of all maps } g(x) : \Sigma \rightarrow G, g \neq \text{constant}\} \quad (145)$$

(The subscript is to emphasize that we exclude constant g 's.) The true configuration space should be $\mathfrak{C} = \mathfrak{F}/\mathfrak{G}_*$.

8.1 Analysis on $S^2 \times \mathbb{R}$

We will now consider a simple special case, namely, $\Sigma = S^2$. We will carry out the analysis on the space of potentials, imposing the condition to eliminate gauge freedom later. Notice that (143) is defined on \mathfrak{F} ; this is the phase space of the theory before reduction by the action of gauge symmetries. The symplectic two-form Ω is given by $\delta\mathcal{A}$, i.e.,

$$\begin{aligned}\Omega &= -\frac{ik}{\pi} \int_{\Sigma} d\mu_{\Sigma} \operatorname{Tr}(\delta A_{\bar{z}} \delta A_z) \\ &= \frac{ik}{2\pi} \int_{\Sigma} d\mu_{\Sigma} \delta A_{\bar{z}}^a \delta A_z^a\end{aligned}\quad (146)$$

(We do not write the wedge sign for exterior products on the field space from now on since it is clear from the context.)

The complex structure on Σ induces a complex structure on \mathfrak{F} . We may take $A_z, A_{\bar{z}}$ as the local complex coordinates on \mathfrak{F} . Indeed we have a Kähler structure on \mathfrak{F} , Ω/k being the Kähler form with the Kähler potential

$$K = \frac{k}{2\pi} \int_{\Sigma} A_{\bar{z}}^a A_z^a \quad (147)$$

The Hamiltonian vector fields corresponding to A_z and $A_{\bar{z}}$ are

$$A_z^a(z) \longrightarrow -\frac{2\pi}{ik} \frac{\delta}{\delta A_z^a}, \quad A_{\bar{z}}^a(z) \longrightarrow \frac{2\pi}{ik} \frac{\delta}{\delta A_{\bar{z}}^a} \quad (148)$$

The Poisson brackets for $A_{\bar{z}}, A_z$ are obtained using the general formula (11) as

$$\begin{aligned}\{A_z^a(z), A_w^b(w)\} &= 0 \\ \{A_{\bar{z}}^a(z), A_w^b(w)\} &= 0 \\ \{A_z^a(z), A_w^b(w)\} &= -\frac{2\pi i}{k} \delta^{ab} \delta^{(2)}(z-w)\end{aligned}\quad (149)$$

These become commutation rules upon quantization. Gauge transformations are given by

$$A^g = g A g^{-1} - dg g^{-1} \quad (150)$$

The infinitesimal version of this (for $g \approx 1 - it_a \theta^a$) is generated by the vector field

$$\xi = - \int_{\Sigma} ((D_z \theta)^a \frac{\delta}{\delta A_z^a} + (D_{\bar{z}} \theta)^a \frac{\delta}{\delta A_{\bar{z}}^a}) \quad (151)$$

where D_z and $D_{\bar{z}}$ denote the corresponding gauge covariant derivatives. By contracting this with Ω we get

$$i_{\xi} \Omega = -\delta \left[\frac{ik}{2\pi} \int_{\Sigma} F_{z\bar{z}}^a \theta^a \right] \quad (152)$$

which shows that the generator of infinitesimal gauge transformations is

$$G^a = \frac{ik}{2\pi} F_{z\bar{z}}^a \quad (153)$$

Reduction of the phase space to gauge-invariant degrees of freedom can thus be performed by setting $F_{z\bar{z}}$ to zero. This takes us from \mathfrak{F} to $\mathfrak{C} = \mathfrak{F}/\mathfrak{G}_*$. The constraint $G^a = 0$ is just the Gauss law of the Chern-Simons gauge theory. Notice also that in the $A_0 = 0$ gauge, the equations of motion (140) tell us that $A_z, A_{\bar{z}}$ are independent of time, but must satisfy the constraint

$$F_{\bar{z}z} \equiv \partial_{\bar{z}} A_z - \partial_z A_{\bar{z}} + [A_{\bar{z}}, A_z] = 0 \quad (154)$$

This is the equation of motion for the A_0^a component. We see that the constraint which reduces the phase space to the physical degrees of freedom is just the equation of motion for A_0^a . Notice also that, for finite transformations, we get

$$\begin{aligned} \Omega(A^g) - \Omega(A) &= \delta \left[\frac{ik}{\pi} \int_{\Sigma} \text{Tr}(g^{-1} \delta g F_{z\bar{z}}) \right] \\ &= \delta \left[-\frac{k}{2\pi} \int_{\Sigma} \text{Tr}(g^{-1} \delta g F) \right] \end{aligned} \quad (155)$$

(In the second term F is the two-form $dA + A \wedge A$.)

The construction of the wave functions proceeds as follows. One has to consider a line bundle on the phase space with curvature Ω . Sections of this bundle give the prequantum Hilbert space. In other words we consider functionals $\Phi[A_z, A_{\bar{z}}]$ with the condition that under the canonical transformation $\mathcal{A} \rightarrow \mathcal{A} + \delta\Lambda$, $\Phi \rightarrow e^{i\Lambda} \Phi$. The inner product on the prequantum Hilbert space is given by

$$(1|2) = \int d\mu(A_z, A_{\bar{z}}) \Phi_1^*[A_z, A_{\bar{z}}] \Phi_2[A_z, A_{\bar{z}}] \quad (156)$$

where $d\mu(A_z, A_{\bar{z}})$ is the Liouville measure associated with Ω . Given the Kähler structure Ω/k , this is just the volume $[dA_z dA_{\bar{z}}]$ associated with the metric $\|\delta A\|^2 = \int_{\Sigma} \delta A_{\bar{z}} \delta A_z$.

The wave functions so constructed depend on all phase space variables. We must now choose the polarization conditions on the Φ 's so that they depend only on half the number of phase space variables. This reduction of the prequantum Hilbert space leads to the Hilbert space of the quantum theory. Given the Kähler structure of the phase space, the most appropriate choice is the Bargmann polarization which can be implemented as follows. With a specific choice of $\rho[A]$ in (143), the symplectic potential can be taken as

$$\mathcal{A} = -\frac{ik}{2\pi} \int_{\Sigma} \text{Tr}(A_{\bar{z}} \delta A_z - A_z \delta A_{\bar{z}}) = \frac{ik}{4\pi} \int_{\Sigma} (A_{\bar{z}}^a \delta A_z^a - A_z^a \delta A_{\bar{z}}^a) \quad (157)$$

The covariant derivatives with \mathcal{A} as the potential are

$$\nabla = \left(\frac{\delta}{\delta A_z^a} + \frac{k}{4\pi} A_z^a \right), \quad \bar{\nabla} = \left(\frac{\delta}{\delta A_{\bar{z}}^a} - \frac{k}{4\pi} A_{\bar{z}}^a \right) \quad (158)$$

The holomorphic (or Bargmann) polarization condition is

$$\nabla \Phi = 0 \quad (159)$$

which has solutions of the form

$$\Phi = \exp\left(-\frac{k}{4\pi} \int A_{\bar{z}}^a A_z^a\right) \psi[A_{\bar{z}}^a] = e^{-\frac{1}{2}K} \psi[A_{\bar{z}}^a] \quad (160)$$

where K is the Kähler potential of (147). The states are represented by wave functionals $\psi[A_{\bar{z}}^a]$ which are holomorphic in $A_{\bar{z}}^a$. Further, the prequantum inner product can be retained as the inner product of the Hilbert space. Rewriting (156) using (160) we get the inner product as

$$\langle 1|2\rangle = \int [dA_{\bar{z}}^a dA_z^a] e^{-K(A_{\bar{z}}^a, A_z^a)} \psi_1^* \psi_2 \quad (161)$$

On the holomorphic wave functionals,

$$A_z^a \psi[A_{\bar{z}}^a] = \frac{2\pi}{k} \frac{\delta}{\delta A_{\bar{z}}^a} \psi[A_{\bar{z}}^a] \quad (162)$$

As we have mentioned before, one has to make a reduction of the Hilbert space by imposing gauge invariance on the states, i.e., by setting the generator $F_{z\bar{z}}^a$ to zero on the wave functionals. This amounts to

$$\left(D_{\bar{z}} \frac{\delta}{\delta A_{\bar{z}}^a} - \frac{k}{2\pi} \partial_z A_{\bar{z}}^a \right) \psi[A_{\bar{z}}^a] = 0. \quad (163)$$

Consistent implementation of gauge invariance can lead to quantization requirements on the coupling constant k . For nonabelian groups G this is essentially the requirement of integrality of k based on the invariance of e^{iS} under homotopically nontrivial gauge transformations. It is the same as the Dirac quantization condition (78). Also, once we impose the gauge invariance condition, the integration in (161) must be restricted to the gauge-invariant volume.

8.2 Argument for quantization of k

We will now work out how the quantization of k arises, in some detail, staying within the geometric quantization framework. Since we are on S^2 , the group of gauge transformations $\mathfrak{G}_* = \{g(x) : S^2 \rightarrow G, g \neq \text{constant}\}$. We have chosen $G = SU(N)$, so obviously

$$\Pi_0(\mathfrak{G}_*) = \Pi_2(G) = 0, \quad \Pi_1(\mathfrak{G}_*) = \Pi_3(G) = \mathbb{Z} \quad (164)$$

Correspondingly one has

$$\Pi_1(\mathfrak{F}/\mathfrak{G}_*) = 0, \quad \Pi_2(\mathfrak{F}/\mathfrak{G}_*) = \mathbb{Z} \quad (165)$$

The nontriviality of $\Pi_2(\mathfrak{F}/\mathfrak{G}_*)$ arises from the nontrivial elements of $\Pi_1(\mathfrak{G}_*)$. Therefore consider a noncontractible loop C of gauge transformations,

$$C = g(x, \alpha), \quad 0 \leq \alpha \leq 1, \quad \text{with } g(x, 0) = g(x, 1) = 1 \quad (166)$$

With the boundary condition given, $g(x, \alpha)$ may be considered as a map from S^3 to G . Such elements fall into homotopy classes corresponding to $\Pi_3(G) = \mathbb{Z}$. We can now use this $g(x, \alpha)$ to construct a noncontractible two-surface in the gauge-invariant space $\mathfrak{F}/\mathfrak{G}_*$. We start with a square in the space of gauge potentials parametrized by $0 \leq \alpha, \sigma \leq 1$ with the potentials given by

$$A(x, \alpha, \sigma) = (g A g^{-1} - dg g^{-1}) \sigma + (1 - \sigma) A \quad (167)$$

We can simplify this even further by taking $A = 0$, so that

$$A(x, \alpha, \sigma) = -\sigma dg g^{-1} \quad (168)$$

This potential goes to zero on the boundaries $\alpha = 0$ and $\alpha = 1$ and also on $\sigma = 0$. A goes to the pure gauge $-dg g^{-1}$ at $\sigma = 1$, which is gauge-equivalent to $A = 0$. Thus the boundary corresponds to a single point on the quotient $\mathfrak{F}/\mathfrak{G}_*$ and we have a closed two-surface. This surface is noncontractible if we take $g(x, \alpha)$ to be a nontrivial element of $\Pi_3(G) = \mathbb{Z}$ since the contraction of the two-surface would constitute a homotopy mapping g to the identity; this is impossible if g belongs to a nontrivial element of $\Pi_3(G)$. Using this set of configurations in Ω and carrying out the integration over σ we get

$$\int \Omega = 2\pi k Q[g] \quad (169)$$

where

$$Q[g] = \frac{1}{24\pi^2} \int \text{Tr}(dgg^{-1})^3 \quad (170)$$

$Q[g]$ is the winding number (which is an integer) characterizing the class in $\Pi_1(\mathfrak{G}_*) = \Pi_3(G)$ to which g belongs. From (78) we know that the integral of Ω over any closed noncontractible two-surface in the phase space must be an integer. Thus (169) and (170) lead to the requirement that k has to be an integer. The parameter k is referred to as the *level number* of the Chern-Simons theory. (Even though we presented the arguments for quantization of the coefficient of the action for $\Sigma = S^2$, similar arguments and results hold more generally.)

8.3 The ground state wave function

We now turn to the solution of (163). For this we introduce the Wess-Zumino-Witten action given by [16, 13]

$$\begin{aligned}\mathcal{S}_{WZW} &= \frac{1}{8\pi} \int_{\Sigma} d^2x \sqrt{g} g^{ab} \text{Tr}(\partial_a K \partial_b K^{-1}) + \Gamma[K] \\ \Gamma[K] &= \frac{i}{12\pi} \int_{\mathcal{M}^3} \text{Tr}(K^{-1} dK)^3\end{aligned}\quad (171)$$

The fields are matrices K which can generally belong to $GL(N, \mathbb{C})$. Also Σ is the two-dimensional space on which the fields are defined. Since it can in general be a curved manifold, we use the two-dimensional metric tensor g_{ab} . (g^{ab} is the inverse metric and g denotes the determinant of g_{ab} as a matrix.) (This model can be defined and used for fields on \mathbb{R}^2 as well, by choosing the boundary condition $K \rightarrow 1$ (or some fixed value independent of directions) as $|\vec{x}| \rightarrow \infty$; topologically, such fields are equivalent to fields on the closed manifold S^2 .)

The second term in the action, $\Gamma[K]$, is the so-called Wess-Zumino term. It is defined in terms of integration over a three-dimensional space \mathcal{M}^3 which has Σ as its boundary. The integrand does not require metrical factors for the integration since it is a differential three-form. However, it requires an extension of the field K to the three-space \mathcal{M}^3 . There can be many spaces \mathcal{M}^3 with the same boundary Σ , or equivalently, there can be many different ways to extend the fields to the three-space \mathcal{M}^3 . The physical results of the theory are independent of how this extension is chosen, if we consider actions of the form $k \mathcal{S}_{WZW}$ where k is an integer. By direct calculation, we can verify the Polyakov-Wiegmann identity

$$\mathcal{S}_{WZW}[K h] = \mathcal{S}_{WZW}[K] + \mathcal{S}_{WZW}[h] - \frac{1}{\pi} \int_{\Sigma} \text{Tr}(K^{-1} \partial_{\bar{z}} K \partial_z h h^{-1}) \quad (172)$$

where we have used local complex coordinates. Now, in two dimensions, we can parametrize a nonabelian gauge potential as

$$A_z = -\partial_z M M^{-1}, \quad A_{\bar{z}} = M^{\dagger-1} \partial_{\bar{z}} M^{\dagger} \quad (173)$$

where M is a complex matrix which may be taken to be in $SL(N, \mathbb{C})$ for gauge fields corresponding to the gauge group $SU(N)$. The identity (172) shows that

$$\delta \mathcal{S}_{WZW} = \mathcal{S}_{WZW}[M^{\dagger} (1 + \theta)] - \mathcal{S}_{WZW}[M^{\dagger}] = \frac{1}{\pi} \int \text{Tr}(\partial_z A_{\bar{z}} \theta) \quad (174)$$

With $D_{\bar{z}}$ denoting the covariant derivative with respect to $A_{\bar{z}}$, we have the identity

$$\partial_z A_{\bar{z}} = D_{\bar{z}}(M^{\dagger-1} \partial_z M^{\dagger}) \quad (175)$$

Notice that, since $\delta M^\dagger = M^\dagger \theta$, we may write $\theta = M^{\dagger-1} \delta M^\dagger$; further, from (173), $\delta A_{\bar{z}} = D_{\bar{z}}(M^{\dagger-1} \delta M^\dagger) = D_{\bar{z}} \theta$. Combining these relations with (175), we can simplify (174) as

$$D_{\bar{z}} \frac{\delta \mathcal{S}_{WZW}}{\delta A_{\bar{z}}^a} = \frac{1}{2\pi} \partial_z A_{\bar{z}}^a \quad (176)$$

where we have also evaluated the trace in terms of the components. Comparing this with (163), we see that we can solve it as

$$\psi(A_{\bar{z}}) = \mathcal{N} \exp \left(k \mathcal{S}_{WZW}[M^\dagger] \right) \quad (177)$$

The normalization factor \mathcal{N} is to be fixed by using the inner product (161). There is only one state for this theory. On S^2 , there are no degrees of freedom left for the Chern-Simons theory after one reduces to the physical configuration space. Thus there is only the vacuum state of the theory. What we have found is the expression for the ground state wave function in terms of the variables on \mathfrak{F} . If we consider higher genus Riemann surfaces, or two-manifolds with a boundary, then the Chern-Simons theory will have nontrivial degrees of freedom.

8.4 Abelian theory on the torus

We will now consider an Abelian Chern-Simons theory, with $G = U(1)$ and with Σ being a torus $S^1 \times S^1$. This will illustrate some of the topological features we mentioned. The torus can be described by $z = \xi_1 + \tau \xi_2$, where ξ_1, ξ_2 are real and have periodicity of $\xi_i \rightarrow \xi_i + \text{integer}$, and τ , which is a complex number, is the modular parameter of the torus. The metric on the torus is $ds^2 = |d\xi_1 + \tau d\xi_2|^2$. The two basic noncontractible cycles of the torus are usually labelled as the α and β cycles. Further the torus has a holomorphic one-form ω with

$$\int_{\alpha} \omega = 1, \quad \int_{\beta} \omega = \tau \quad (178)$$

Since ω is a zero mode of $\partial_{\bar{z}}$, we can parametrize $A_{\bar{z}}$ as

$$A_{\bar{z}} = \partial_{\bar{z}} \chi + i \frac{\pi \bar{\omega}}{\text{Im} \tau} a \quad (179)$$

where χ is a complex function and a is a complex number corresponding to the value of $A_{\bar{z}}$ along the zero mode of $\partial_{\bar{z}}$.

For this space $\Pi_0(\mathfrak{G}_*) = \mathbb{Z} \times \mathbb{Z}$, because the gauge transformations $g_{m,n}$ can have nontrivial winding numbers m, n around the two cycles. Consider one connected component of \mathfrak{G}_* , say $\mathfrak{G}_{m,n}$. A homotopically nontrivial $U(1)$ transformation can be written as $g_{m,n} = e^{i\alpha} e^{i\theta_{m,n}}$, where $\alpha(z, \bar{z})$ is a homotopically trivial gauge transformation and

$$\theta_{m,n} = \frac{i\pi}{\text{Im} \tau} \left[m \int^z \bar{\omega} - \omega + n \int^z \tau \bar{\omega} - \bar{\tau} \omega \right], \quad m, n \in \mathbb{Z} \quad (180)$$

With the parametrization of $A_{\bar{z}}$ as in (179), the effect of this gauge transformation can be represented as

$$\chi \rightarrow \chi + \alpha, \quad a \rightarrow a + m + n\tau \quad (181)$$

The real part of χ can be set to zero by an appropriate choice of α . (The imaginary part also vanishes when we impose the condition $F_{z\bar{z}} = 0$.) The physical subspace (which has only the zero modes left after reduction) is given by the values of a modulo the transformation (181), or in other words,

$$\text{Physical space for zero modes} \equiv \mathfrak{C} = \frac{\mathbb{C}}{\mathbb{Z} + \tau\mathbb{Z}} \quad (182)$$

This space is known as the Jacobian variety of the torus. It is also a torus and therefore we see that the phase space \mathfrak{C} has nontrivial Π_1 and \mathcal{H}^2 . In particular, $\Pi_1(\mathfrak{C}) = \mathbb{Z} \times \mathbb{Z}$ and this leads to two angular parameters φ_α and φ_β which are the phases the wave functions acquire under the gauge transformation $g_{1,1}$. The symplectic two-form can be written as

$$\begin{aligned} \Omega &= \frac{k}{4\pi} \int \bar{\partial}\delta\chi \wedge \partial\delta\bar{\chi} + \frac{k\pi}{4} \frac{d\bar{a} \wedge da}{\text{Im}\tau} \int_{\Sigma} \frac{\bar{\omega} \wedge \omega}{\text{Im}\tau} \\ &= \Omega_\chi - i \frac{k\pi}{2} \frac{d\bar{a} \wedge da}{\text{Im}\tau} \end{aligned} \quad (183)$$

Integrating the zero mode part over the physical space of zero modes \mathfrak{C} , we get

$$\int_{\mathfrak{C}} \Omega = k\pi \quad (184)$$

showing that k must be quantized as an even integer for $U(1)$ fields on the torus due to (78).⁸

The modular parameter of the torus is subject to the so-called modular transformations which are homotopically nontrivial diffeomorphisms of the torus. The vacuum angles change under such transformations and can eventually be set to zero. To continue with the quantization, we focus on the zero modes for which the symplectic potential can be written as

$$\mathcal{A} = -\frac{\pi k}{4} \frac{(\bar{a} - a)(\tau d\bar{a} - \bar{\tau} da)}{\text{Im}\tau} \quad (185)$$

The polarization condition then becomes

$$\left[\frac{\partial}{\partial \bar{a}} + i \frac{\pi k (\bar{a} - a) \tau}{4 (\text{Im}\tau)^2} \right] \Psi = 0 \quad (186)$$

⁸Since there has been some argument over this point in the literature, a comment might be in order. In geometric quantization, we are considering the wave functions as sections of a line bundle. This means that each quantum state has a wave function which is a complex number. One can avoid the quantization condition on k for the Abelian theory if one is willing to go beyond this and allow for multicomponent wave functions (for each state). However, the interpretation of such wave functions is not very clear.

with the solution

$$\Psi = \exp \left[-i \frac{\pi k (\bar{a} - a)^2 \tau}{8 (\text{Im}\tau)^2} \right] f(a) \quad (187)$$

where $f(a)$ is holomorphic in a . Under the gauge transformation (181) we find

$$\Psi(a + m + n\tau) = \exp \left[-i \frac{\pi k (\bar{a} - a)}{8 (\text{Im}\tau)^2} - \frac{\pi k n (\bar{a} - a) \tau}{\text{Im}\tau} + i \pi k \tau n^2 \right] f(a + m + n\tau) \quad (188)$$

Under this gauge transformation \mathcal{A} changes by $d\Lambda_{m,n}$ where

$$\Lambda_{m,n} = i \frac{\pi k n (\tau \bar{a} - \bar{\tau} a)}{2 \text{Im}\tau} \quad (189)$$

The change in Ψ should thus be given by $\exp(i\Lambda_{m,n})\Psi$; requiring the transformation (188) to be equal to this, we get

$$f(a + m + n\tau) = \exp \left[-i \frac{\pi k n^2 \tau}{2} - \frac{2\pi i k n a}{2} \right] f(a) \quad (190)$$

This transformation rule shows that $f(a)$ is a Jacobi Θ -function. On these functions $f(a)$, \bar{a} is realized as $(2 \text{Im}\tau / k\pi)(\partial/\partial a) + a$. The inner product for the wave functions of the zero modes is

$$\langle f|g \rangle = \int \exp \left[-\frac{\pi k \bar{a} a}{2 \text{Im}\tau} + \frac{\pi k \bar{a}^2}{4 \text{Im}\tau} + \frac{\pi k a^2}{4 \text{Im}\tau} \right] \bar{f} g \quad (191)$$

It is then convenient to absorb the holomorphic part of the exponent into the wave function defining the new set of holomorphic wave functions

$$\Phi \equiv \exp \left[\frac{\pi k a^2}{4 \text{Im}\tau} \right] f(a) = \exp \left[\frac{\pi k a^2}{4 \text{Im}\tau} \right] \Theta(a) \quad (192)$$

On these functions, \bar{a} acts as

$$\bar{a} = \frac{2 \text{Im}\tau}{\pi k} \frac{\partial}{\partial a} \quad (193)$$

The key point we wanted to illustrate here is the use of the homotopically nontrivial gauge transformations.

9 θ -vacua in a nonabelian gauge theory

Consider a nonabelian gauge theory in four spacetime dimensions, the gauge group is some compact Lie group G . We can choose the gauge where $A_0 = 0$ so that there are only the three spatial components of the gauge potential, namely, A_i , considered as an antihermitian Lie algebra valued vector field.. The choice $A_0 = 0$ does not completely fix the gauge, one can still do gauge transformations which are independent of time. These are given by

$$A_i \rightarrow A'_i = g A_i g^{-1} - \partial_i g g^{-1} \quad (194)$$

The Yang-Mills action gives the symplectic two-form as

$$\Omega = \int d^3x \delta E_i^a \delta A_i^a = -2 \int d^3x \text{Tr} (\delta E_i \delta A_i) \quad (195)$$

where E_i^a is the electric field $\partial_0 A_i^a$, along the Lie algebra direction labelled by a . The gauge transformation of E_i is $E_i \rightarrow g E_i g^{-1}$. By combining this with the transformation (194), we identify the vector field generating infinitesimal gauge transformations, with $g \approx 1 + \varphi$, as

$$\xi = - \int d^3x \left[(D_i \varphi)^a \frac{\delta}{\delta A_i^a} + [E_i, \varphi]^a \frac{\delta}{\delta E_i^a} \right] \quad (196)$$

This leads to

$$i_\xi \Omega = -\delta \int d^3x [-(D_i \varphi)^a E_i^a] \quad (197)$$

The generator of time-independent gauge transformations is thus

$$G(\varphi) = - \int d^3x (D_i \varphi)^a E_i^a \quad (198)$$

For transformations which go to the identity at spatial infinity, $G^a = (D_i E_i)^a$. This is Gauss law, one of the Yang-Mills equations of motion. This is to be viewed as a condition on the allowed initial data and enforces a reduction of the phase space to gauge invariant variables. We again define the space of fields and gauge transformations as

$$\mathfrak{F} = \left\{ \text{space of gauge potentials } A_i \right\} \quad (199)$$

$$\mathfrak{G}_* = \left\{ \begin{array}{l} \text{space of gauge transformations } g(\vec{x}) : \mathbb{R}^3 \rightarrow G \\ \text{such that } g \rightarrow 1 \text{ as } |\vec{x}| \rightarrow \infty \end{array} \right\} \quad (200)$$

The transformations $g(\vec{x})$ which go to a constant element $g_\infty \neq 1$ act as a Noether symmetry. The states fall into unitary irreducible representations of such transformations, which are isomorphic to the gauge group G , upto \mathfrak{G}_* -transformations. The true gauge freedom is only \mathfrak{G}_* . The physical configuration space of the theory is thus $\mathfrak{C} = \mathfrak{F}/\mathfrak{G}_*$.⁹

With the boundary condition on the g 's, the gauge functions are equivalent to a map from S^3 to G , and hence there are homotopically distinct transformations corresponding to the fact that $\Pi_3(G) = \mathbb{Z}$. (In other words, $\Pi_0(\mathfrak{G}_*) = \mathbb{Z}$.) These can be labelled by the winding number $Q[g]$ given in (170). We can write \mathfrak{G}_* as the sum of different components, each of which is connected and is characterized by the winding number Q . i.e.,

$$\mathfrak{G}_* = \sum_{Q=-\infty}^{+\infty} \oplus \mathfrak{G}_Q \quad (201)$$

⁹For further elaboration on this question, see [3] and references therein.

where each \mathfrak{G}_Q consists of all maps with winding number Q . \mathfrak{G}_Q and $\mathfrak{G}_{Q'}$ are disconnected from each other for $Q \neq Q'$, since if they are connected, $g_Q \in \mathfrak{G}_Q$ and $g_{Q'} \in \mathfrak{G}_{Q'}$ should be deformable to each other and this is impossible since $Q \neq Q'$. One can easily check that $Q[g g'] = Q[g] + Q[g']$ and hence this structure is isomorphic to the additive group of integers \mathbb{Z} . The space of gauge potentials \mathfrak{F} is an affine space and is topologically trivial. Combining these facts, we see that the configuration space has noncontractible loops, with $\Pi_1(\mathfrak{C}) = \Pi_3(G) = \mathbb{Z}$.

An example of a noncontractible loop in \mathfrak{C} is as follows. Let $g_1(x)$ be a gauge transformation with winding number 1 and consider the line in \mathcal{A} given by

$$A_i(x, \tau) = A_i(x)(1 - \tau) + A_i^{g_1} \tau \quad (202)$$

for $0 \leq \tau \leq 1$ or more generally

$$A_i(x, \tau) \text{ with } A_i(x, 0) = A_i(x), \quad A_i(x, 1) = A_i^{g_1}(x) \quad (203)$$

where $A_i^{g_1}$ is the gauge transform of A_i by $g_1(x)$. This is an open path in \mathfrak{F} . But since $A_i^{g_1}$ is the gauge transform of A_i , both configurations A_i and $A_i^{g_1}$ represent the same point in $\mathfrak{C} = \mathfrak{F}/\mathfrak{G}_*$. Thus $A_i(x, \tau)$ describes a closed loop in \mathfrak{C} . If this loop is contractible, we can deform the trajectory to a curve purely along the gauge flow directions which connects $g = 1$ to $g_1(x)$. This would imply that $g_1(x)$ is smoothly deformable to the identity. But this is impossible from our discussion of the structure of \mathfrak{G}_* . In turn this implies that $A_i(x, \tau)$ of (203) is a noncontractible loop. By considering other values of the winding number, we can easily establish that $\Pi_1(\mathfrak{C}) = \mathbb{Z}$. Our general discussion shows that there must be an angle θ which appears in the quantum theory. We can see how this emerges by writing the symplectic potential.

We will first construct a flat potential on the space of fields. For this we start with the instanton number which is given, for a four-dimensional potential, by

$$\begin{aligned} \nu[A] &= -\frac{1}{8\pi^2} \int d^4x \operatorname{Tr} (F_{\mu\nu} F_{\alpha\beta}) \epsilon^{\mu\nu\alpha\beta} \\ &= \frac{1}{16\pi^2} \int d^4x E_i^a F_{jk}^a \epsilon^{ijk} \end{aligned} \quad (204)$$

The density in the above integral is a total derivative in terms of the potential A , but it cannot be written as a total derivative in terms of gauge-invariant quantities. $\nu[A]$ is an integer for any field configuration which is nonsingular up to gauge transformations. It is possible to construct configurations which have nonzero value of ν which are nonsingular; these are instantons in a general sense.¹⁰ An example of a $\nu = 1$ configuration, for $G = SU(2)$, is

$$A_\mu(x) = \frac{x^2}{x^2 + \alpha^2} \omega^{-1} \partial_\mu \omega, \quad \omega = \frac{x_4 + i \vec{\sigma} \cdot \vec{x}}{\sqrt{x^2}} \quad (205)$$

¹⁰There is a more specific sense in which the word instanton is used; it applies to self-dual solutions of the Yang-Mills equations which further have $\nu[A] \neq 0$.

For our purpose, we can transform this to the gauge with $A_0 = A_4 = 0$ obtaining

$$\begin{aligned} A_i &= U \left(\frac{ix^2}{x^2 + \alpha^2} \omega^{-1} \partial_i \omega \right) U^{-1} - \partial_i U U^{-1}, & U &= \exp(i\vec{\sigma} \cdot \hat{x} \rho) \\ \rho &= \frac{|\vec{x}|}{\sqrt{|\vec{x}|^2 + \alpha^2}} \left[\arctan \left(\frac{x_4}{\sqrt{|\vec{x}|^2 + \alpha^2}} \right) - \frac{\pi}{2} \right], & \frac{\partial \rho}{\partial x_4} &= \frac{|\vec{x}|}{x^2 + \alpha^2} \end{aligned} \quad (206)$$

Here σ_i are the Pauli matrices and the path is parametrized by x_4 , $-\infty \leq x_4 \leq \infty$. $x^2 = \vec{x}^2 + x_4^2$. Since x_4 parametrizes the path, we see that $\nu[A]$ can be written as

$$\begin{aligned} \nu[A] &= \oint K[A] \\ K[A] &= \int d^3x F_{jk}^a \delta A_i^a \epsilon^{ijk} \end{aligned} \quad (207)$$

The integral of the one-form K around a closed curve is the instanton number ν and is nonzero, in particular, for the loop corresponding to (206). We can also see that the one-form $K[A]$ on \mathfrak{C} is closed in the following way.

$$\begin{aligned} \delta K[A] &= -2 \int d^3x \delta \left(\text{Tr} (F_{jk} \delta A_i) \right) \epsilon^{ijk} = -4 \int d^3x \text{Tr} ((D_j \delta A_k) \delta A_i) \epsilon^{ijk} \\ &= -4 \int d^3x \text{Tr} (\partial_j \delta A_k \delta A_i + [A_j, \delta A_k] \delta A_i) \epsilon^{ijk} \\ &= 0 \end{aligned} \quad (208)$$

In the last step we have used the antisymmetry of the expression under permutation of δ 's, cyclicity of the trace and have done a partial integration. We see from the above discussion that $K[A]$ is a closed one-form which is not exact since its integral around the closed curves can be nonzero.

With this flat potential on \mathfrak{C} , we can construct a general solution for the symplectic potential corresponding to the Ω in(195) as

$$\mathcal{A} = \int d^3x E_i^a \delta A_i^a + \theta K[A] \quad (209)$$

Use of this potential will lead to a quantum theory where we need the parameter θ , in addition to other parameters such as the coupling constant, to characterize the theory. The potential \mathcal{A} in (209) is obtained from an action

$$\mathcal{S} = -\frac{1}{4} \int d^4x F_{\mu\nu}^a F^{a\mu\nu} + \theta \nu[A] \quad (210)$$

This shows that the effect of using (209) can be reproduced in the functional integral approach by using the action (210). Since it is $\exp(i\mathcal{S})$ which is important, we see that θ is an angle with

values $0 \leq \theta < 2\pi$. Alternatively, we can see that one can formally eliminate the θ -term in \mathcal{A} by making a transformation $\Psi \rightarrow \exp(i\theta\Lambda)\Psi$ where

$$\Lambda = -\frac{1}{8\pi^2} \int \text{Tr} \left(A \wedge dA + \frac{2}{3} A \wedge A \wedge A \right) \quad (211)$$

Notice that $2\pi\Lambda$ is the Chern-Simons action (139) for $k = 1$. Λ is not invariant under homotopically nontrivial transformations. The wave functions get a phase equal to $e^{i\theta Q}$ under the winding number Q -transformation, showing that θ can be restricted to the interval indicated above. This is in agreement with our discussion after equation (72).

10 Fractional statistics in quantum Hall effect

Excitations in the fractional quantum Hall effect will provide another example of how the non-trivial connectivity of the configuration space can affect the physics. We will discuss this briefly now. The simplest and best description we have so far for the fractional quantum Hall effect is in terms of the many-electron wave functions [18]. For example, for the states with filling fractions $\nu = 1/(2p + 1)$ where p is an integer, the N -electron wave function is usually taken as the Laughlin function

$$\Psi_{Laughlin} = \mathcal{N} \exp \left(-\frac{1}{2} \sum_{i=1}^N \bar{z}_i z_i \right) \prod_{1 \leq i < j \leq N} (z_i - z_j)^{2p+1} \quad (212)$$

where $z = x_1 + ix_2$. and the subscript refers to the particle. This leads to an electric current of the form

$$\langle J_i \rangle = -\nu \frac{e^2}{2\pi} \epsilon_{ij} E_j, \quad \nu = \frac{1}{2p + 1} \quad (213)$$

This corresponds to the observed Hall conductivity, quantized as the reciprocals of odd integers. Among the excited states of the system are hole-like excitations with a wave function of the form

$$\begin{aligned} \Psi_{hole} &= \prod_{i=1}^N (z_i - w) \Psi_{Laughlin} \\ &= \prod_{i=1}^N (z_i - w) \mathcal{N} \exp \left(-\frac{1}{2} \sum_{i=1}^N \bar{z}_i z_i \right) \prod_{1 \leq i < j \leq N} (z_i - z_j)^{2p+1} \end{aligned} \quad (214)$$

where w is the position of the hole. We want to briefly consider the statistics of holes in fractional quantum Hall effect. We can do this in an effective description with an action of the form

$$S = \int d^3x \left[\frac{k}{4\pi} \epsilon^{\mu\nu\alpha} a_\mu \partial_\nu a_\alpha + a_\mu \left(j^\mu - \frac{e}{2\pi} \epsilon^{\mu\nu\alpha} \partial_\nu A_\alpha \right) \right] \quad (215)$$

where a^μ ($\mu = 0, 1, 2$) is a new auxiliary field and j^μ denotes the hole current. The value of the constant k will be specified shortly. A_μ is the electromagnetic vector potential. (We are using a three-dimensional covariant notation now. $B^0 = \epsilon^{0ij} \partial_i A_j$ is the magnetic field along the x_3 -axis.) The variation of the action with respect to A_α identifies the electromagnetic current as

$$J^\alpha = -\frac{e}{2\pi} \epsilon^{\alpha\mu\nu} \partial_\mu a_\nu \quad (216)$$

The equation of motion for the auxiliary field a_μ is

$$\frac{k}{2\pi} \epsilon^{\mu\nu\alpha} \partial_\nu a_\alpha + j^\mu - \frac{e}{2\pi} \epsilon^{\mu\nu\alpha} \partial_\nu A_\alpha = 0 \quad (217)$$

From (216) and this equation, we see that

$$J^\mu = \frac{e}{k} j^\mu - \frac{e^2}{2\pi k} \epsilon^{\mu\nu\alpha} \partial_\nu A_\alpha. \quad (218)$$

Choosing $k = 2p + 1$ we see that we can reproduce the Hall conductivity correctly in the absence of holes. The first term then shows that the charge per hole is e/k .

For a pair of well-separated holes we can take

$$j^\mu = \dot{w}_1^\mu \delta^{(2)}(x - w_1) + \dot{w}_2^\mu \delta^{(2)}(x - w_2) \quad (219)$$

Leaving the electromagnetic field and focusing on the holes, the action becomes

$$S_{hole} = \frac{k}{4\pi} \int d^3x \epsilon^{\mu\nu\alpha} a_\mu \partial_\nu a_\alpha + \int dt \left(a_\mu(w_1) \dot{w}_1^\mu + a_\mu(w_2) \dot{w}_2^\mu + \frac{m\dot{w}_1^2}{2} + \frac{m\dot{w}_2^2}{2} \right) \quad (220)$$

where we have also added a regular kinetic energy term for the holes. (The specific form of this will not be important for our purpose.) The time-component of the equation of motion for a_μ , namely (217), can be simplified as

$$\partial_z \alpha_{\bar{z}} - \partial_{\bar{z}} a_z = -i \frac{\pi}{k} \left(\delta^{(2)}(x - w_1) + \delta^{(2)}(x - w_2) \right) \quad (221)$$

Using

$$\partial_z \frac{1}{\bar{z} - \bar{w}} = \partial_{\bar{z}} \frac{1}{z - w} = \pi \delta^{(2)}(x - w) \quad (222)$$

the solution to (221) can be worked out as

$$a_{\bar{z}} = -\frac{i}{2k} \left(\frac{1}{\bar{z} - \bar{w}_1} + \frac{1}{\bar{z} - \bar{w}_2} \right), \quad a_z = \frac{i}{2k} \left(\frac{1}{z - w_1} + \frac{1}{z - w_2} \right) \quad (223)$$

The coincident point $w_1 = w_2$ has to be excluded for consistency. We will also use the $a_0 = 0$ gauge so that the action (220) for the holes simplifies to

$$S = \int dt \left[\frac{m}{2} (\dot{w}_1 \dot{w}_1 + \dot{w}_2 \dot{w}_2) + a_{w_1} \dot{w}_1 + a_{\bar{w}_1} \dot{\bar{w}}_1 + a_{w_2} \dot{w}_2 + a_{\bar{w}_2} \dot{\bar{w}}_2 \right] \quad (224)$$

where we have removed the singularities at the poles; in (224),

$$\begin{aligned} a_{w_1} &= \frac{i}{2k} \frac{1}{w_1 - w_2}, & a_{\bar{w}_1} &= -\frac{i}{2k} \frac{1}{\bar{w}_1 - \bar{w}_2} \\ a_{w_2} &= \frac{i}{2k} \frac{1}{w_2 - w_1}, & a_{\bar{w}_2} &= -\frac{i}{2k} \frac{1}{\bar{w}_2 - \bar{w}_1} \end{aligned} \quad (225)$$

The two equations (224) and (225) suffice for our consideration of the statistics of holes.

Because the coincident point $w_1 = w_2$ has been excluded, the closed path of one hole going around the other is not smoothly deformable to zero. Thus Π_1 of the configuration space is nonzero, equal to \mathbb{Z} . In fact, with w_2 fixed,

$$a_{w_1} dw_1 + a_{\bar{w}_1} d\bar{w}_1 = d \left[\frac{i}{2k} \log \left(\frac{w_1 - w_2}{\bar{w}_1 - \bar{w}_2} \right) \right] \quad (226)$$

This is evidently closed, but cannot be considered exact since

$$\oint_C a = -\frac{2\pi}{k} \neq 0 \quad (227)$$

where C is a contour enclosing w_2 .

The Hamiltonian corresponding to the action (224) is

$$H = \frac{1}{2} m (\dot{w}_1 \dot{w}_1 + \dot{\bar{w}}_2 \dot{\bar{w}}_2) \quad (228)$$

From the action we also identify the operators

$$\begin{aligned} m\dot{w}_1 &= -i \frac{\partial}{\partial \bar{w}_1} - a_{\bar{w}_1}, & m\dot{\bar{w}}_1 &= -i \frac{\partial}{\partial w_1} - a_{w_1} \\ m\dot{w}_2 &= -i \frac{\partial}{\partial \bar{w}_2} - a_{\bar{w}_2}, & m\dot{\bar{w}}_2 &= -i \frac{\partial}{\partial w_2} - a_{w_2} \end{aligned} \quad (229)$$

Written as a differential operator, the Hamiltonian will involve the a 's. Because of this, it is convenient to write the wave function as

$$\Psi(x_1, x_2) = \exp \left[\frac{1}{2k} \log \left(\frac{\bar{w}_1 - \bar{w}_2}{w_1 - w_2} \right) \right] \Phi(x_1, x_2) \quad (230)$$

The action of H on Φ is then the usual one,

$$H \Phi = -\frac{1}{2m} \left(\frac{\partial}{\partial w_1} \frac{\partial}{\partial \bar{w}_1} + \frac{\partial}{\partial w_2} \frac{\partial}{\partial \bar{w}_2} \right) \Phi \quad (231)$$

We can now consider the exchange of the two holes as due to a rotation of the two points by π followed by a translation to bring them back to the same points. We take Φ to be symmetric

under exchange. As for the phase factor in (230), the translation does not change it. The π -rotation leads to

$$\Psi(x_2, x_1) = e^{-i\pi/k} \Psi(x_1, x_2) \quad (232)$$

With $k = 2p + 1$, we see that the two holes do display fractional statistics. The origin of this can be traced to the closed but not exact one-form (226).

In two spatial dimensions, it is also possible to have fractional values for the spin for a particle [19]. The usual argument for the quantization for spin in three spatial dimensions relies on the fact that the components of the angular momentum operators do not commute among themselves and because we need a unitary representation. In two spatial dimensions, there is only one rotation and fractional values for spin are possible. This is true even in a Lorentz-invariant theory, because of the noncompact nature of the Lorentz group. There is a spin-statistics theorem in two spatial dimensions as well. In accordance with this, the result we have shown implies that the holes have fractional spins or that they are “anyons” [19].

11 Fluid dynamics

We now turn to considerations about how an action for fluid dynamics can be constructed using the results on quantization of G/H spaces and how anomalies can be incorporated into fluid dynamics [20]. We start with the well known formulation of classical nonrelativistic fluid dynamics.

11.1 The Lagrange formulation

The so-called Lagrange formulation of fluid dynamics, developed more than two centuries ago by Euler and Lagrange, is an elegant method of obtaining the equations of fluid dynamics starting from Newton’s equations for point-particles. Here one considers a collection of, say, N particles obeying the equations of motion

$$\frac{d}{dt} \dot{X}_\lambda^i = -\frac{\partial V}{\partial X_{i\lambda}} \quad (233)$$

where X_λ^i denote the position of the λ -th particle, $\lambda = 1, 2, \dots, N$. For simplicity, we have taken all particles to have the same mass m , with units adjusted so that $m = 1$. We can label the particles by their positions at time $t = 0$, assuming that there is no overlap of particles. In the limit of a large number of particles, this means that we may take λ to be continuous; it is a three-vector corresponding to the initial position vector. Let $\rho_0(\lambda)$ be the number density of particles.

Then we sum equation (233) over a small range of λ and go to the continuous λ -limit to obtain

$$\rho_0(\lambda) d^3\lambda \frac{d}{dt} \dot{X}^i(t, \lambda) = -\rho_0(\lambda) d^3\lambda \frac{\partial V}{\partial X_i(t, \lambda)} \quad (234)$$

Now, the particle at position $\vec{\lambda}$ at $t = 0$ moves to $X^i(t, \lambda)$ at time t . This is a continuous transformation of the λ^i into X^i , which is invertible at least for small t . We can therefore solve for λ^i as a function of X^i and t and write various quantities as functions of t, X^i . Since the number of particles is conserved, we should have $\rho_0(\lambda) d^3\lambda = \rho(t, X) d^3X$. This shows that we can define the density of particles in terms of X as

$$\rho(t, X) = \frac{\rho_0(\lambda)}{\det(\partial X / \partial \lambda)} \quad (235)$$

The density ρ so defined obeys an equation of continuity. By direct differentiation with respect to time, we find

$$\begin{aligned} \frac{\partial \rho}{\partial t} + \frac{\partial \rho}{\partial X^i} \dot{X}^i &= \rho_0(\lambda) \frac{d}{dt} \frac{1}{\det(\partial X / \partial \lambda)} = -\frac{\rho_0(\lambda)}{\det(\partial X / \partial \lambda)} \frac{d}{dt} (\log \det(\partial X / \partial \lambda)) \\ &= -\rho \frac{\partial \lambda^i}{\partial X^k} \frac{\partial \dot{X}^k}{\partial \lambda^i} = -\rho \nabla_k \dot{X}^k \end{aligned} \quad (236)$$

We now define the velocity at a point X as

$$v^i(t, X) = \dot{X}^i(t, \lambda) \Big|_{\lambda=\lambda(t, X)} \quad (237)$$

Equation (236) then reduces to the continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla_k (\rho v^k) = 0 \quad (238)$$

The equation of motion (234) involves the time-derivative of the velocity $\dot{X}^i(t, \lambda)$. We can substitute for λ in terms of X in this equation. Thus the quantity on the left hand side involves

$$\left. \frac{d}{dt} \dot{X}^i(t, \lambda) \right|_{\lambda=\lambda(t, X)} = \left. \frac{d}{dt} \dot{X}^i(t, \lambda(t, X)) \right|_{\lambda \text{ fixed}} \quad (239)$$

In other words, we should substitute $\lambda = \lambda(t, X)$ after the second time-derivative has been evaluated. Since λ^i do not depend on time, being initial data, we get the identity

$$0 = \frac{\partial \lambda^i(t, X)}{\partial t} + \frac{\partial \lambda^i(t, X)}{\partial X^k} \dot{X}^k \quad (240)$$

Simplifying (239) using (240), the equation of motion (234) becomes

$$\rho \left[\frac{\partial v^i}{\partial t} + v^k \nabla_k v^i \right] = -\rho \frac{\partial V}{\partial X_i(t, \lambda)} \quad (241)$$

This equation, along with the continuity equation (238), defines perfect fluid dynamics. The right hand side of (241) can be expressed in terms of the gradient of the pressure, but we will not need that for now.

In modern physics, a point-particle is defined as a unitary irreducible representation of the Poincaré group. In addition, we may want to consider particles with internal symmetries such as nonabelian color charges, the latter being also described by an appropriate representation of the symmetry group. So we may ask:

Can we do a Lagrange trick and describe fluid dynamics in terms of group theory, with each particle corresponding to a unitary irreducible representation of the symmetry group (Poincaré \otimes internal symmetry group)?

We can also equally well ask the counter question: Why would this be interesting beyond the pure mathematical joy of showing that it can be done? There are some good reasons. In such a formalism, symmetry would be really foundational and this would facilitate the inclusion of nonabelian internal symmetries and spin in magnetohydrodynamics and also incorporate anomalous symmetries as well. These have all become issues of interest in recent research partly because of the deconfined fluid phase of quarks and gluons.

We start with a simple case of a nonrelativistic particle which carries an internal symmetry, say, $SU(2)$ to see how this can all work out. (This internal symmetry could be “color” or spin or something else depending on the physical context.) The action for such a particle coupled to an $SU(2)$ gauge field is given by

$$\begin{aligned} \mathcal{S} &= \int dt \left[\frac{1}{2} m \dot{x}^2 - A_i^a Q^a \dot{x}_i - i \frac{n}{2} \text{Tr}(\sigma_3 g^{-1} \dot{g}) \right] \\ &= \int dt \left[\frac{1}{2} m \dot{x}^2 - i \frac{n}{2} \text{Tr}(\sigma_3 g^{-1} D_0 g) \right] \end{aligned} \quad (242)$$

where $Q^a = \frac{n}{4} \text{Tr}(\sigma_3 g^{-1} \sigma^a g)$ and $D_0 = \partial_0 + A_i^a \dot{x}_i (-i \sigma^a / 2)$. D_0 is the covariant derivative of g with respect to the $SU(2)$ gauge field evaluated on the trajectory of the particle. This action was proposed in the 1970s by Balachandran and collaborators [7]; the equations of motion corresponding to this action were written down earlier, in 1971, by Wong [21]. The last term in (242), apart from the gauge field term, is familiar to us as the action (114) for $G/H = SU(2)/U(1)$. The quantization of the action is also familiar. The usual kinetic term $\frac{1}{2} m \dot{x}^2$ will lead to the usual point particle dynamics, with a minimal coupling to the gauge field via the charge operator Q^a . The degrees of freedom represented by g will lead to a unitary representation of $SU(2)$, with $j = n/2$. This part will describe the dynamics of the internal symmetry and how it influences and is influenced by the kinetic motion of the particle and the external field.

We can now see how to generalize to fluids. We will focus on the last term in (242) as it is the key term for obtaining UIRs of the group after quantization. We consider a large number of particles, using a variable λ to label them. As with the Lagrangian approach to fluids, we will eventually take λ to be continuous and to correspond to a three-volume. For the last term in (242) we get

$$\mathcal{S} = -i \frac{n}{2} \int dt \operatorname{Tr}(\sigma_3 g^{-1} \dot{g}) \longrightarrow \mathcal{S} = -\frac{i}{2} \int dt \sum_{\lambda} n_{\lambda} \operatorname{Tr}(\sigma_3 g_{\lambda}^{-1} \dot{g}_{\lambda}) \quad (243)$$

We can take the continuum limit by $\sum_{\lambda} \rightarrow \int J d^3x/v$, where J is the Jacobian of the transformation $\vec{\lambda} \rightarrow \vec{x}$, $J = |\partial\lambda/\partial x|$ and v indicates a small volume over which the dynamics is coarse-grained. Defining a density by $j^0 = n J/v$, we get

$$\mathcal{S} = -i \int d^4x j^0 \operatorname{Tr}(t_3 g^{-1} \partial_0 g), \quad t_3 = \frac{\sigma_3}{2} \quad (244)$$

where $g(t, \lambda) = g(t, \vec{x})$ is to be considered as a spacetime-dependent group element. The form of the action (244) also suggests a natural relativistic generalization

$$\mathcal{S} = -i \int j^{\mu} \operatorname{Tr}(t_3 g^{-1} \partial_{\mu} g) \quad (245)$$

The remaining terms in the action can be added on at this stage, but before doing that, we pause to consider what happens with the Poincaré group. If we follow the same strategy we should consider the analog of the term $\operatorname{Tr}(t_3 g^{-1} \dot{g})$ for the Poincaré group, which has the translational parameters x^{μ} and the rotational and Lorentz boost parameters; the latter set of parameters may be gathered into a Lorentz group element Λ . The action is then given by

$$S = - \int d\tau p_{\mu} \dot{x}^{\mu} + i \frac{n}{4} \int d\tau \operatorname{Tr}(\Sigma_3 \Lambda^{-1} \dot{\Lambda}) \quad \Sigma_3 = \begin{bmatrix} \sigma_3 & 0 \\ 0 & \sigma_3 \end{bmatrix} \quad (246)$$

where we have chosen to display the term involving the Lorentz group element Λ in terms of the usual spinor representation.¹¹ This is almost what we want, but the first term in the action (246) is a bit awkward. In going over to a fluid description, the position variables x^{μ} are a bit awkward. First of all, there should only be three independent x 's or corresponding velocities. For the point-particle, this is naturally implemented by a mass-shell type constraint. It is not clear how to do this for fluids. Secondly, the role of diffeomorphisms versus translations is not clear in this language. So we will first deal with this problem before returning to the main line of development.

¹¹This is like using the 2×2 -matrix version of g to display the action (242). It does not imply that there is anything special about this representation.

11.2 Clebsch variables and the general form of action

We return to the usual approach to fluids briefly. It has been known for a long time that fluid dynamics can be described as a Poisson bracket system. This means that the equations of motion are derived from a Hamiltonian

$$H = \int d^3x \left[\frac{1}{2} \rho v^2 + V(\rho) \right] \quad (247)$$

by using the Poisson brackets

$$\begin{aligned} [\rho(x), \rho(y)] &= 0 \\ [v_i(x), \rho(y)] &= \partial_{x_i} \delta^{(3)}(x - y) \\ [v_i(x), v_j(y)] &= -\frac{\omega_{ij}}{\rho} \delta^{(3)}(x - y) \end{aligned} \quad (248)$$

The pressure is related to $V(\rho)$ as $p = \rho \frac{\partial V}{\partial \rho} - V$. The Poisson brackets can be summarized for arbitrary functions F, G of the fluid variables as

$$[F, G] = \int \left[\frac{\delta F}{\delta \rho} \partial_i \left(\frac{\delta G}{\delta v_i} \right) - \frac{\delta G}{\delta \rho} \partial_i \left(\frac{\delta F}{\delta v_i} \right) - \frac{\omega_{ij}}{\rho} \frac{\delta F}{\delta v_i} \frac{\delta G}{\delta v_j} \right] \quad (249)$$

It is then easy to check that any local observable F will Poisson commute with the helicity which is defined as

$$C = \frac{1}{12\pi^2} \int \epsilon^{ijk} v_i \partial_j v_k \quad (250)$$

where we take the velocity to vanish at the boundary of the spatial region of integration. Denoting the variables ρ, v_i collectively as q^μ , and writing the Poisson brackets as $\{q^\mu, q^\nu\} = K^{\mu\nu}$, we can check from (249) that $\delta C / \delta v_i$ is a zero mode for $K^{\mu\nu}$. This means that $K^{\mu\nu}$ is not invertible. Comparing with (12) we see that we have a problem. If $K^{\mu\nu}$ has an inverse, that would be the symplectic structure $\Omega_{\mu\nu}$ and we can construct an action. But that is not possible because $K^{\mu\nu}$ has a zero mode. This is a problem, but the way to a solution is also clear. Since C Poisson commutes with any local observable, it must be superselected. We must fix its value and then consider only those velocities which keep the value unchanged. Such a parametrization is given by the Clebsch variables which expresses the velocity as

$$v_i = \partial_i \theta + \alpha \partial_i \beta \quad (251)$$

where θ, α and β are 3 independent fields. One can easily check that the integrand of C is a total derivative with this parametrization and gives zero upon integration. (We can also accommodate other values of C , see below.) A suitable action which gives the fluid equations is then

$$\mathcal{S} = \int d^4x \left[\rho \dot{\theta} + \rho \alpha \dot{\beta} \right] - \int d^4x \left[\frac{1}{2} \rho v^2 + V \right] \quad (252)$$

We can also write this as

$$\mathcal{S} = \int d^4x [j^\mu (\partial_\mu \theta + \alpha \partial_\mu \beta)] - \int d^4x \left[j^0 - \frac{j^i j^i}{2\rho} + V \right] \quad (253)$$

where $j^0 = \rho$ and we introduce an auxiliary field \vec{j} . Elimination of \vec{j} takes us back to (252). This is easily generalized to the relativistic case as

$$S = \int d^4x [j^\mu (\partial_\mu \theta + \alpha \partial_\mu \beta) - F(n)] \quad (254)$$

where $F(n) = n + V(n)$ and $n^2 = j^2 = (j^0)^2 - j^i j^i$. Notice that $n = \sqrt{(j^0)^2 - \vec{j} \cdot \vec{j}} \approx j^0 - (j^i j^i / 2j^0) + \dots$, so that (253) is recovered in the nonrelativistic case.

The Clebsch parametrization can also be written in a more group-theoretic form. For this purpose, we can use either $SU(1, 1)$ or $SU(2)$. We parametrize an element of the group as¹²

$$g = \frac{1}{\sqrt{1 \mp \bar{u}u}} \begin{pmatrix} 1 & u \\ \pm \bar{u} & 1 \end{pmatrix} \begin{pmatrix} e^{i\theta} & 0 \\ 0 & e^{-i\theta} \end{pmatrix}, \quad (255)$$

We can easily check that

$$-i \operatorname{Tr} \left(\frac{\sigma_3}{2} g^{-1} dg \right) = d\theta + \alpha d\beta, \quad \alpha = \frac{\bar{u}u}{(1 \mp \bar{u}u)}, \quad \beta = \mp \frac{i}{2} \log(u/\bar{u}) \quad (256)$$

where the upper sign applies to $SU(1, 1)$ and the lower to $SU(2)$.¹³ We can now write the usual ordinary fluid dynamics action as

$$\mathcal{S} = \int d^4x [-ij^\mu \operatorname{Tr}(\sigma_3 g^{-1} \partial_\mu g) - F(n)] \quad (257)$$

We have thus brought the action, even for the usual fluid dynamics, to a form consistent with the group-theoretic approach. We can now see how the Poincaré group can be accommodated. For the translational part we use the Clebsch way of writing the action. For the rest of it, we can use the usual group-theoretic way which we have already discussed. Thus our action for a general fluid dynamics is given by

$$\begin{aligned} \mathcal{S} = \int d^4x \left[j^\mu (\partial_\mu \theta + \alpha \partial_\mu \beta) - \frac{i}{4} j_{(s)}^\mu \operatorname{Tr}(\Sigma_3 \Lambda^{-1} \partial_\mu \Lambda) + i \sum_a j_{(a)}^\mu \operatorname{Tr}(q_a g^{-1} D_\mu g) \right. \\ \left. - F(\{n\}) \right] + S(A) \end{aligned} \quad (258)$$

¹²Whether we should choose $SU(1, 1)$ or $SU(2)$ depends on the vorticity which is given as $d\alpha d\beta$. The group $SU(2)$ would describe situations with quantized vorticity, $SU(1, 1)$ would give no quantization condition on vorticity.

¹³By the way, we are also saying that ordinary fluid dynamics can display an $SU(1, 1)$ or $SU(2)$ symmetry, which is effectively replacing the diffeomorphism symmetry. This is a point worth further exploration.

We use q_a to denote the diagonal generators of the internal symmetry group G with $g \in G$. The currents $j^\mu, j_{(s)}^\mu, j_{(a)}^\mu$ correspond to the transport of mass, spin and internal quantum numbers, respectively. Generally, we must have different currents $j^\mu, j_{(s)}^\mu, j_{(a)}^\mu$ for mass flow, spin flow and the transport of other quantum numbers, since they are independent. For example, we may have a cluster of particles of zero total spin moving off in some direction, giving mass transport but no spin transport; we can have a similar situation with internal symmetry groups as well. Generally these currents are independent; any relations among them must be viewed as “constitutive relations” characteristic of the physical system. The coupling of the system to gauge fields follows from covariant derivatives on the group elements. The function $F(\{n\})$ depends on all the invariants such as $n = \sqrt{j^\mu j_\mu}, n_a = \sqrt{j_{(a)}^\mu j_{\mu(a)}},$ etc., which we can make from the currents and the gauge fields. We have explicitly indicated the action for the gauge fields. The group-valued fields are related to flow velocities and currents and are given by the equations of motion,

$$\begin{aligned} \frac{1}{n} \frac{\partial F}{\partial n} j_\mu &= \partial_\mu \theta + \alpha \partial_\mu \beta \\ \frac{1}{n_a} \frac{\partial F}{\partial n_a} j_{\mu(a)} &= i \text{Tr}(q_a g^{-1} D_\mu g), \quad \text{etc.} \end{aligned} \quad (259)$$

11.3 Assorted comments

Many new concepts (or at least concepts which may not be very familiar) have been introduced, so a few clarifying remarks are in order at this point.

Helicity

In terms of the group-valued variables, the helicity is given by the topological invariant

$$C = \frac{1}{24\pi^2} \int \text{Tr}(g^{-1} dg)^3 \quad (260)$$

This shows how we may generalize the Clebsch parametrization to situations with nonzero value of C . We choose a particular g , say g_1 which gives the desired value C . Then we write use $g_1 g$ in place of g in (256) to get the parametrization for velocities. g is taken to have zero C . It is easy to check that $C[g_1 g] = C[g_1] + C[g] = C[g_1]$.

The action and the density matrix

The idea of using an action of the form $\int j^0 \text{Tr}(\sigma_3 g^{-1} \dot{g})$ may be seen from another more general point of view as well. The full quantum dynamics for a state with density matrix ρ is given by the action

$$S = \int dt \text{Tr} \left[\rho_0 \left(U^\dagger i \frac{\partial U}{\partial t} - U^\dagger H U \right) \right] \quad (261)$$

The variational equation for this is

$$i \frac{\partial \rho}{\partial t} = H \rho - \rho H, \quad \rho = U \rho_0 U^\dagger \quad (262)$$

which is the expected equation for the time-evolution of the density matrix. The canonical one-form corresponding to this action is

$$\mathcal{A} = i \text{Tr}(\rho_0 U^\dagger \delta U) \quad (263)$$

where δU includes all possible observables. Consider a subset of transformations (such as symmetry transformations which can survive into the hydrodynamic regime). We write δU as

$$\delta U = -i (t_A U) \delta \theta^A + \text{other transformations} \quad (264)$$

where the other transformations correspond to other observables, beyond the subset we are interested in. Neglecting those, we find that \mathcal{A} restricted to the variables of interest is

$$\mathcal{A} = \text{Tr}(U \rho_0 U^\dagger t_A) \delta \theta^A = T_A \delta \theta^A, \quad T_A(\theta) = \text{Tr}(\rho t_A) = \langle t_A \rangle \quad (265)$$

T_A will have appropriate group composition/commutation properties. θ 's are essentially collective variables for the theory. We can then ask the question: What is the action (at the level of the θ 's) which gives this \mathcal{A} ? This is evidently the co-adjoint orbit action of the form we have been using.

Diffeomorphisms and Clebsch variables

Finally, we can think of the Clebsch variables in another way as well.¹⁴ We start by looking at the diffeomorphism algebra,

$$[M(\xi), M(\xi')] = M(\xi \times \xi'), \quad (\xi \times \xi')^i = \xi^k \partial_k \xi'^i - \xi'^k \partial_k \xi^i \quad (266)$$

where M is the generator of spatial diffeomorphisms, given by T_{0i} where $T_{\mu\nu}$ is the energy-momentum tensor. The algebra (266) can be realized by

$$J_i = \pi_1 \partial_i \varphi_1 + \pi_2 \partial_i \varphi_2 + \dots \quad (267)$$

for any number of canonical pairs of variables (π_i, φ_i) . We need two such pairs for a complete characterization in 3 spatial dimensions. Hence, we can see that diffeomorphism symmetry can be traded for an $SU(1, 1)$ or $SU(2)$ symmetry for the pairs π_i, φ_i . The redesignation of variables as $\pi_1 = \rho, \pi_2 = \rho \alpha, \varphi_1 = \theta, \varphi_2 = \beta$ takes us back to the usual Clebsch form.

¹⁴In principle, we can use the action (246) with the translational degrees of freedom x^μ even in the fluid case. If we keep \dot{x}^μ as fluid velocity, then we do get the correct fluid equations, but with no pressure.

We can also view π_1, φ_1 as the modulus and phase of a complex field ψ, ψ^* . But then how do we interpret the extra fields α, β ? These are what we need to get vorticity. We may observe that for vorticity, we need to compare the velocities of nearby particles. Thus in attributing some nonzero vorticity to each local coarse-graining unit, we see that inside each such unit (around, say, \vec{x}), we must have distinct fields representing these particles whose velocities are to be compared. This means that $\psi(x)$ and $\psi(x + \epsilon)$ must be counted as independent fields since we want to replace them by fields at a single point \vec{x} upon coarse-graining. This gives some understanding of how the $SU(1, 1)$ or $SU(2)$ group emerges.

11.4 Examples

11.4.1 Nonabelian magnetohydrodynamics

We will briefly mention a few examples before going on to the question of anomalies. Our first example is about nonabelian magnetohydrodynamics, say with $SU(2)$ as the internal symmetry [22]. Picking out the relevant terms in the general action (258), we see that we can take the action for this case as

$$\begin{aligned}
\mathcal{S} &= \int J_m^\mu (\partial_\mu \theta + \alpha \partial_\mu \beta) - i \int j^\mu \text{Tr}(\sigma_3 g^{-1} D_\mu g) - \int F(n) + S_{YM} & (268) \\
D_\mu g &= \partial_\mu g + A_\mu g & A_\mu = -i t^a A_\mu^a, \quad t^a = \frac{1}{2} \sigma^a \\
J_m^\mu &= n_m U^\mu, & U^2 = 1 \\
j^\mu &= n u^\mu, & u^2 = 1
\end{aligned}$$

J_m^μ denotes the mass current, while j^μ corresponds to the current for the diagonal generator of the internal symmetry. We have also defined the flow velocities U^μ and u^μ in terms of the currents. The current which couples to the gauge field may be obtained as

$$J_a^\mu = -\frac{\delta \mathcal{S}}{\delta A_\mu^a} = \text{Tr}(\sigma_3 g^{-1} t_a g) j^\mu = Q_a u^\mu, \quad Q_a = n \text{Tr}(\sigma_3 g^{-1} t_a g) \quad (269)$$

Notice that the current factorizes into a charge density Q_a and a flow velocity u^μ . This is known as the Eckart factorization. The equations of motion may be derived from the action (268) by varying all the fields. We show some of the equations here:

$$\begin{aligned}
\partial_\mu j^\mu &= 0 \\
(D_\mu J^\mu)_a &= 0 \\
n u^\mu \partial_\mu (u_\nu F') - n \partial_\nu F' &= \text{Tr}(J^\mu F_{\mu\nu}) & (270)
\end{aligned}$$

The first two are conservation laws, while the last one is the Euler equation for the (nonabelian) charge transport.¹⁵ The first two equations in (270) also give

$$w^\mu (D_\mu Q)_a = (D_0 Q)_a + \vec{u} \cdot (\vec{D} Q)_a = 0 \quad (271)$$

This may be viewed as the fluid version of the Wong equations for the transport of nonabelian charge by a point-particle. We also have $\partial_\mu T^{\mu\nu} = \text{Tr}(J^\mu F_{\mu\nu})$ where the energy-momentum tensor $T_{\mu\nu}$ has the perfect fluid form.

The group element g may be given a nice physical interpretation. The nonabelian charge density $\rho = \rho_a t_a$ (which is the time-component of J_a^μ) transforms, under gauge transformations, as

$$\rho \rightarrow \rho' = h^{-1} \rho h, \quad h \in SU(2) \quad (272)$$

Thus we can diagonalize ρ at each point by an (\vec{x}, t) -dependent transformation g . Then we can write $\rho = g \rho_{diag} g^{-1}$, with $\rho_{diag} = \rho_0 \sigma_3$. In other words,

$$\rho_a = \rho_0 \text{Tr}(g \sigma_3 g^{-1} t_a) = j^0 \text{Tr}(g \sigma_3 g^{-1} t_a) \quad (273)$$

The group element g diagonalizes the charge density at each point. The eigenvalues are gauge-invariant and are represented by n . We may thus view g as describing the degrees of freedom corresponding to the orientation of the local charge density in color space. Under a gauge transformation, $g \rightarrow h^{-1} g$.

The Poisson brackets involving the charge densities are

$$\begin{aligned} \{j^0(\vec{x}), j^0(\vec{y})\} &= 0 \\ \{j^0(\vec{x}), g(\vec{y})\} &= -i g(\vec{x}) \left(\frac{\sigma_3}{2}\right) \delta(x-y) \\ \{\rho_a(\vec{x}), \rho_b(\vec{y})\} &= f_{abc} \rho_c(\vec{x}) \delta(x-y) \\ \{\rho_a(\vec{x}), g(\vec{y})\} &= -i \left(\frac{\sigma_a}{2}\right) g(\vec{x}) \delta(x-y) \end{aligned} \quad (274)$$

Notice that ρ_a generates left transformations on g , while j^0 generates right transformations along the σ_3 -direction.

11.4.2 Spin and fluids

Another example we will briefly quote is for fluids with spin [23]. Consider a special case where mass transport and charge transport are described by the same flow velocity. In other words, impose a ‘‘constitutive relation’’ $J_m^\mu = j_e^\mu$. Such a relation is reasonable when we have one species

¹⁵There is another equation for mass transport which we are not displaying. Here we are zeroing in on just the ‘‘new’’ equations, namely, those beyond the usual ones.

of particles with the same charge. Further, for dilute systems, if we neglect the possibility of spin-singlets forming (and moving independently), we can take spin flow velocity \approx charge flow velocity, so that we can further impose $J_m^\mu = j_s^\mu$. In this case, the action (258) simplifies as

$$S = S(A) + \int d^4x \left[j^\mu (\partial_\mu \theta + \alpha \partial_\mu \beta + e A_\mu) - \frac{i}{4} j^\mu \text{Tr}(\Sigma_3 \Lambda^{-1} \partial_\mu \Lambda) - F(n, \sigma) \right] \quad (275)$$

The Lorentz group element Λ may be written as $\Lambda = B R$, where B is a specific boost transformation taking us from a rest frame to a moving frame and R is a spatial rotation. Explicitly,

$$B(u) = \frac{1}{\sqrt{2(u^0 + 1)}} \begin{bmatrix} u^0 + 1 & \vec{\sigma} \cdot \vec{u} \\ \vec{\sigma} \cdot \vec{u} & u^0 + 1 \end{bmatrix} \quad (276)$$

The statement that $J_m^\mu = j_s^\mu$ means that B contains the same velocity u^μ as for the mass transport, as in $j^\mu = n u^\mu$. F depends on n and $\sigma = S^{\mu\nu} F_{\mu\nu}$, where $S^{\mu\nu}$ is the spin density,

$$S^{\mu\nu} = \frac{1}{2} \text{Tr}(\Sigma_3 \Lambda^{-1} J^{\mu\nu} \Lambda), \quad J^{\mu\nu} = \frac{i}{4} [\gamma^\mu, \gamma^\nu] \quad (277)$$

One interesting feature which emerges from this analysis, and the equations of motion for the action (275), is that the spin density is subject to precession effects due to pressure gradient terms in addition to the expected precession due to the magnetic field. This is seen explicitly from the equations of motion

$$\begin{aligned} u^\alpha \partial_\alpha (F' u_\nu) - \partial_\nu F' &= e u^\lambda F_{\lambda\nu} - \frac{16e}{F'} \partial_\nu S^{\lambda\beta} (S F S - F S S)_{\lambda\beta} + \dots \\ u^\alpha \partial_\alpha S_{\mu\nu} &= \frac{e}{F'} \left[S_\mu^\lambda F_{\lambda\nu} - S_\nu^\lambda F_{\lambda\mu} \right] + \left[S_\mu^\lambda f_{\lambda\nu} - S_\nu^\lambda f_{\lambda\mu} \right] \\ &\quad - \frac{16e}{F'^2} (u_\mu S_\nu^\lambda - u_\nu S_\mu^\lambda) \partial_\lambda S^{\rho\beta} (S F S - F S S)_{\rho\beta} + \dots \end{aligned} \quad (278)$$

where $F' = (\partial F / \partial n)$ and

$$\begin{aligned} f_{\lambda\nu} &= \frac{1}{F'} [u_\lambda \partial_\nu F' - u_\nu \partial_\lambda F'] \\ (S F S - F S S)_{\lambda\beta} &= S_\lambda^\rho F_{\rho\tau} S_\beta^\tau - F_\lambda^\rho S_{\rho\tau} S_\beta^\tau \end{aligned} \quad (279)$$

The first equation in (278) is the expected Lorentz force formula for fluids, with corrections depending on the gradient of the spin density. The second describes the precession of the spin density in the electromagnetic field. The term $S_\mu^\lambda f_{\lambda\nu} - S_\nu^\lambda f_{\lambda\mu}$ describes a spin precession effect due to pressure gradient terms which can exist even in the absence of external fields. This is a bit unusual and somewhat unexpected.

11.5 Anomalies

We will now consider how anomalies can affect fluid dynamics. Anomalies arise in the quantum theory because of the need to regularize the theory. This involves a cut-off on the integrations over loop momenta in various Feynman diagrams. If a situation arises that one cannot find a regulator which preserves all the classical symmetries, then we have to ensure that the regulator we choose preserves gauge symmetries (for consistency reasons). This may mean that we have to give up some of the other non-gauge symmetries. We say that those symmetries are anomalous.

Even though anomalies arise out of ultraviolet regulators, they have a deeper topological origin and one consequence of this aspect of the anomalies is that they are not renormalized. Further, they can also be reproduced from infrared physics. As a result, we can expect them to be relevant in the hydrodynamical regime as well.

11.5.1 Anomalous electrodynamics

First of all we will consider a very simple case, that of an Abelian $U(1)$ theory which has anomalies. We may think of this as electromagnetism. The basic equations we need are the conservation laws,

$$\begin{aligned}\partial_\mu T_\nu^\mu &= F_{\lambda\mu} J^\mu \\ \partial_\mu J^\mu &= -\frac{c}{8}\epsilon^{\mu\nu\alpha\beta} F_{\mu\nu} F_{\alpha\beta}\end{aligned}\tag{280}$$

The first equation is the expected relation for the divergence of the energy-momentum tensor. The second one is the conservation law for charge which is anomalous, with the anomaly as given on the right hand side. Here c is a constant, the anomaly coefficient, which can be calculated from the underlying quantum physics. The lack of conservation for the electric current will, of course, lead to inconsistencies, so we must really regard this system as describing a subsystem which is anomalous, with another subsystem which will cancel this anomaly for the full system, thus avoiding any inconsistencies. These two equations (280) are to be supplemented by the form of T_ν^μ and J^μ , given by

$$\begin{aligned}T_\nu^\mu &= \mu n U^\mu U_\nu + \delta_\nu^\mu P \\ J^\mu &= n U^\mu + \epsilon^{\mu\nu\alpha\beta} \left[\frac{c}{6} \mu U_\nu \partial_\alpha (\mu U_\beta) + \frac{c}{2} \mu U_\nu \partial_\alpha A_\beta \right]\end{aligned}\tag{281}$$

where μ is the chemical potential corresponding to the particle number and P is the pressure. Notice that T_ν^μ has the perfect fluid form. These equations (280) and (281) were written down

by Son and Surowka as a minimal way to incorporate anomalies [24]. We may then ask the question: Can we find an action which leads to these equations? We may expect such an action in terms of the formalism we have developed. Indeed such an action can be found, it is given by

$$\mathcal{S} = \int d^4x \left[j^\mu (V_\mu + A_\mu) + \frac{c}{6} \epsilon^{\mu\nu\alpha\beta} (A_\mu V_\nu \partial_\alpha V_\beta + V_\mu A_\nu \partial_\alpha A_\beta) - \mu \sqrt{-j^2} + P(\mu) \right] \quad (282)$$

where $V_\mu = \partial_\mu \theta + \alpha \partial_\mu \beta$ and the flow velocity U^μ is related to V_μ by

$$(V + A)_\mu = -\mu U_\mu \quad (283)$$

It is not difficult to see why the action is of the form (282). The terms representing the anomaly must be independent of the metric, and hence it must be a differential four-form. The only one-forms available are the electromagnetic gauge potential $A = A_\mu dx^\mu$ and the velocity of the fluid for which we can use the Clebsch form, $V = V_\mu dx^\mu = d\theta + \alpha d\beta$. Thus we can take a linear combination of $A V dV$ and $V A dA$. The coefficients can be fixed by comparison with (280) and (281). This leads to the action (282). The equations which follow from this action have been analyzed in more detail in [25].

11.5.2 Anomalies in the fluid phase of the standard model

A more interesting scenario is where there are no gauge anomalies and we ask the question of how we can include the anomalies for the non-gauge symmetries. The most physical realization of this would be the standard model, so we will phrase our arguments in terms of it. We may regard the fluid we are talking about as the quark-gluon plasma phase for three flavors of quarks, say, u, d, s . In other words, we consider a phase with thermalized u, d, s quarks, so that they must be described by fluid variables while the heavier quarks are described by the field corresponding to each species. We will also neglect the quark masses so that we have the full flavor symmetry $U(3)_L \times U(3)_R$. Thus the group G to be used in (258) is

$$G = SU(3)_c \times U(3)_L \times U(3)_R \quad (284)$$

with individual flows corresponding to the charges. Here we want to focus on the flavor transport, as this is the sector with anomalies, so we will drop the color group $SU(3)_c$ from the equations to follow.

The flavor symmetry is not fully preserved even in the absence of masses; this is because of the anomalies. It may be useful at this point to recall the argument why we expect a term in the effective action which reproduces anomalies [26]. We set up a *gedanken* argument, where we consider all flavor symmetries to be gauged with their anomalies canceled by an extra set

of fermions; the latter will not play any role in the dynamics except for the anomalies, so they are referred to as spectator fermions. The full theory is nonanomalous. The usual argument is that if, instead of the quarks, we consider the confined phase with mesons and baryons as the basic degrees of freedom, the theory will continue to remain nonanomalous. Even though the confined phase is obtained only at low energy, anomalies, because of their topological origin, are unaffected. Thus in the effective action for baryons and mesons, we should be able to find a term which reproduces the original anomalies, thereby ensuring cancellation with the spectator fermions. This is the Wess-Zumino term written in terms of the pseudoscalar meson fields. Clearly, we can expect a similar reasoning for the fluid phase where u, d, s are replaced by fluid variables. We must then have a term in the fluid action which can reproduce the anomalies so that the cancellation with spectator fermions still remains valid. How do we write this term? Since we have formulated fluid dynamics in terms of group-valued variables, the solution is almost trivial. We can simply use the usual Wess-Zumino term, but interpret the group-valued variables in it, not in terms of mesons, but as describing the fluid flow velocities for various flavor quantum numbers.

Adapting (258) to the case at hand with $U(3)_L \times U(3)_R$ symmetry, the action for fluid phase of the standard model is [28]

$$\begin{aligned}
\mathcal{S} = & -i \int \left[j_3^\mu \text{Tr} \left(\frac{\lambda_3}{2} g_L^{-1} D_\mu g_L \right) + j_8^\mu \text{Tr} \left(\frac{\lambda_8}{2} g_L^{-1} D_\mu g_L \right) + k_3^\mu \text{Tr} \left(\frac{\lambda_3}{2} g_R^{-1} D_\mu g_R \right) \right. \\
& \left. + k_8^\mu \text{Tr} \left(\frac{\lambda_8}{2} g_R^{-1} D_\mu g_R \right) + j_0^\mu \text{Tr} (g_L^{-1} D_\mu g_L) + k_0^\mu \text{Tr} (g_R^{-1} D_\mu g_R) \right] \\
& - F(n_3, n_8, n_0, m_3, m_8, m_0) + S_{YM}(A) + \Gamma_{WZ}(A_L, A_R, g_L g_R^\dagger) - \Gamma_{WZ}(A_L, A_R, \mathbb{1})
\end{aligned} \tag{285}$$

The three diagonal generators correspond to the t_3, t_8 and the identity for $U(3)_L$ and $U(3)_R$, with the corresponding currents $j_3^\mu, j_8^\mu, j_0^\mu$ and $k_3^\mu, k_8^\mu, k_0^\mu$. We have also defined $n_l^2 = j_l^2, m_l^2 = k_l^2$ with $l = 0, 3, 8$. $g_L \in U(3)_L$ and $g_R \in U(3)_R$ will describe the various flow velocities; their relation to the currents is seen upon eliminating the latter by the equations of motion. Further, $\Gamma_{WZ}(A_L, A_R, g_L g_R^\dagger)$ is the standard Wess-Zumino term $\Gamma_{WZ}(A_L, A_R, U)$ with $U \implies g_L g_R^\dagger$. We have also subtracted $\Gamma_{WZ}(A_L, A_R, \mathbb{1})$ which is necessary to bring the analysis to the so-called Bardeen form of the anomalies [27]. The Bardeen form is the one which not only preserves the vector gauge symmetries, but also gives a manifestly vector-gauge-invariant form to the remaining axial anomalies. This form is what is appropriate for the fluid phase. The explicit expression for $\Gamma_{WZ}(A_L, A_R, g_L g_R^\dagger)$ is

$$\Gamma_{WZ} = -\frac{iN}{240\pi^2} \int_D \text{Tr}(dU U^{-1})^5 - \frac{iN}{48\pi^2} \int_{\mathcal{M}} \text{Tr}[(A_L dA_L + dA_L A_L + A_L^3) dU U^{-1}]$$

$$\begin{aligned}
& -\frac{iN}{48\pi^2} \int_{\mathcal{M}} \text{Tr}[(A_R dA_R + dA_R A_R + A_R^3) U^{-1} dU] \\
& +\frac{iN}{96\pi^2} \int_{\mathcal{M}} \text{Tr}[A_L dUU^{-1} A_L dUU^{-1} - A_R U^{-1} dU A_R U^{-1} dU] \\
& +\frac{iN}{48\pi^2} \int_{\mathcal{M}} \text{Tr}[A_L (dUU^{-1})^3 + A_R (U^{-1} dU)^3 + dA_L dU A_R U^{-1} - dA_R d(U^{-1}) A_L U] \\
& +\frac{iN}{48\pi^2} \int_{\mathcal{M}} \text{Tr}[A_R U^{-1} A_L U (U^{-1} dU)^2 - A_L U A_R U^{-1} (dUU^{-1})^2] \tag{286} \\
& -\frac{iN}{48\pi^2} \int_{\mathcal{M}} \text{Tr}[(dA_R A_R + A_R dA_R) U^{-1} A_L U - (dA_L A_L + A_L dA_L) U A_R U^{-1}] \\
& -\frac{iN}{48\pi^2} \int_{\mathcal{M}} \text{Tr}[A_L U A_R U^{-1} A_L dUU^{-1} + A_R U^{-1} A_L U A_R U^{-1} dU] \\
& -\frac{iN}{48\pi^2} \int_{\mathcal{M}} \text{Tr}[A_R^3 U^{-1} A_L U - A_L^3 U A_R U^{-1} + \frac{1}{2} U A_R U^{-1} A_L U A_R U^{-1} A_L]
\end{aligned}$$

with $U \implies g_L g_R^\dagger$. (N is the number of colors, = 3 for us.) This is evidently a very complicated expression and we will need to pick out some pieces to highlight some physical effects. The most relevant of such effects is the chiral magnetic effect.

11.5.3 The chiral magnetic effect

The chiral magnetic effect corresponds to the following. In the quark-gluon plasma, in the presence of a magnetic field, there is charge separation and a chiral induction which may be displayed as

$$J_0 = \frac{e^2}{2\pi^2} \nabla \theta \cdot \vec{B}, \quad J_i = -\frac{e^2}{2\pi^2} \dot{\theta} B_i \tag{287}$$

Here θ is an axial $U(1)$ field, similar to the η' -meson. In the plasma, we can replace $\dot{\theta}$ by the difference of the chemical potentials corresponding to the $U(1)_L$ and $U(1)_R$ subgroups of $U(3)_L \times U(3)_R$ as $\dot{\theta} \rightarrow \frac{1}{2}(\mu_L - \mu_R)$. In this case, we find

$$J_i = -\frac{e^2}{4\pi^2} (\mu_L - \mu_R) B_i \tag{288}$$

We see that the chiral asymmetry of chemical potentials can lead to an electromagnetic current in the direction of the magnetic field [29]. In the experiment with colliding heavy nuclei which produces this fluid phase, if the collision is slightly off-center, the two nuclei constitute a current which produces, for a very short time, an intense magnetic field of the order of $10^{17} G$. The resulting current can be expected to produce an asymmetry in the charge distribution of particles coming out, with more above the plane of collision than below it.¹⁶ Such an asymmetry

¹⁶“Above” means in the direction of the magnetic field.

is indeed experimentally observed; however, there are other possible explanations for it. So it is not entirely clear if it can be attributed to the chiral magnetic effect. Nevertheless, let us see how this effect can be obtained from the Wess-Zumino term (286).

The original calculation of the chiral magnetic effect is via Feynman diagrams, but we can easily see it from our action (285). We calculate the electromagnetic current from the Wess-Zumino term, and then restrict to two flavors, taking U to be of the form

$$U = e^{i\theta} \begin{bmatrix} V & 0 \\ 0 & 1 \end{bmatrix} \quad (289)$$

The current is given by

$$\begin{aligned} J^\mu &= J_3^\mu + \frac{e}{48\pi^2} \epsilon^{\mu\nu\alpha\beta} \text{Tr}(\mathcal{I}_\nu \mathcal{I}_\alpha \mathcal{I}_\beta) + i \frac{e^2}{16\pi^2} \epsilon^{\mu\nu\alpha\beta} \partial_\nu A_\alpha \text{Tr}[(\Sigma_{3L} + \Sigma_{3R}) I_\beta] + J_\theta^\mu \\ J_\theta^\mu &= -\frac{e^2}{4\pi^2} \epsilon^{\mu\nu\alpha\beta} \partial_\nu A_\alpha \partial_\beta \theta \left[2 + \frac{1}{4} \text{Tr}(\Sigma_{3L} \Sigma_{3R} - 1) \right] \end{aligned} \quad (290)$$

where J_3^μ is the contribution from the usual non-anomalous terms in (285) and

$$\mathcal{I}_\beta = g_L^{-1} \partial_\beta g_L - g_R^{-1} \partial_\beta g_R, \quad \Sigma_{3L} = g_L^{-1} \sigma_3 g_L, \quad \Sigma_{3R} = g_R^{-1} \sigma_3 g_R \quad (291)$$

If we further restrict to $g_L = g_R$ (effectively setting $V = 1$ at this stage) we get

$$\begin{aligned} J_\theta^\mu &= -\frac{e^2}{2\pi^2} \epsilon^{\mu\nu\alpha\beta} (\partial_\nu A_\alpha) \partial_\beta \theta \\ J_i &= -\frac{e^2}{4\pi^2} (\mu_L - \mu_R) B_i \end{aligned} \quad (292)$$

In the second line, we wrote out J_i and replaced $\dot{\theta}$ by $\frac{1}{2}(\mu_L - \mu_R)$. This equation reproduces the chiral magnetic effect [29]. The full set of equations are necessary to describe full hydrodynamic transport of flavor charges.

There are many other anomaly related effects, such as a possible pion asymmetry [28] or chiral vorticity effects. But the present discussion suffices to illustrate the main issues of principle.

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12 Practice problems

Problem 1

Our general formulation of quantization in terms of Ω can be applied in many unusual situations. A simple example is the light-cone quantization of a scalar field.

We have introduced light-cone coordinates, corresponding to a light-cone in the z -direction in (34). Consider the evolution of the fields in u , with the other light-cone coordinate v and the two coordinates $x^T = x, y$ transverse to the light-cone playing the role of space. They correspond to equal- u hypersurfaces. The action for a scalar field and the canonical 1-form were also given in (35) and (37). Show that the Poisson brackets are given by

$$\{\varphi(u, v, x^T), \varphi(u, v', x'^T)\} = -\frac{1}{4}\epsilon(v - v') \delta^{(2)}(x^T - x'^T) \quad (293)$$

and that the Hamiltonian for u -evolution is given by

$$H = \int dv d^2x^T \left[\frac{1}{2}(\partial_T \varphi)^2 + U(\varphi) \right] \quad (294)$$

Here $\epsilon(v - v')$ is the signature function, equal to 1 for $v - v' > 0$ and equal to -1 for $v - v' < 0$.

Problem 2

Verify that ξ_{\pm}, ξ_3 in (100) are indeed Hamiltonian vector fields for Ω given in (90) with the corresponding functions J_{\pm}, J_3 as in (101).

Problem 3

Consider a map $\mathbb{R}^3 \rightarrow SU(2)$ given by

$$U(x) = \cos F(r) + i\sigma_i \frac{x_i}{r} \sin F(r) \quad (295)$$

where $F(r)$ is a function of the radial variable r . This can be considered as a map from S^3 to $SU(2)$ only if $\sin F$ is zero at $r = 0, \infty$; why? Using the formula (170) for the winding number show that

$$Q[U] = \frac{1}{\pi} (F(0) - F(\infty)) \quad (296)$$

Show also, using (170), that

$$Q[g g'] = Q[g] + Q[g'] \quad (297)$$

Problem 4

Check the inner product (161) by verifying that A, \bar{A} are indeed adjoints with this inner product.

Problem 5

Verify the Polyakov-Wiegmann identity (172) and use it to show that

$$k \mathcal{S}_{WZW}(M) + k \mathcal{S}_{WZW}(M^\dagger) - K(A_z, A_{\bar{z}}) = k \mathcal{S}_{WZW}(M^\dagger M) \quad (298)$$

Problem 6

Starting from the action (252), obtain the canonical two-form for fluids and verify the Poisson brackets (248).

Problem 7

The calculation of the Poisson brackets (274) is a bit trickier. One needs to obtain the Ω corresponding to (268) and calculate the Hamiltonian vector fields corresponding to various quantities listed in (274). Carry through this calculation to obtain the PBs.

Problem 8

We have considered the geometric quantization of $\mathbb{C}\mathbb{P}^2$ considered as $SU(3)/U(2)$. One can also consider $\mathbb{C}\mathbb{P}^2$ in terms of local complex coordinates, just as we did in the case of $\mathbb{C}\mathbb{P}^1$. The symplectic 2-form can be written in local coordinates as

$$\Omega = -i n \left[\frac{dz_i \wedge d\bar{z}_i}{(1 + \bar{z} \cdot z)} - \frac{dz_i \bar{z}_i \wedge z_k d\bar{z}_k}{(1 + \bar{z} \cdot z)^2} \right] \quad (299)$$

where $i, k = 1, 2$ and $\bar{z} \cdot z = \bar{z}_1 z_1 + \bar{z}_2 z_2$. (This is valid for one coordinate patch of $\mathbb{C}\mathbb{P}^2$, but this should be adequate for what follows.) Carry out the quantization in this language, by identifying the covariant derivatives, the holomorphic polarization condition, etc. Show that the resulting Hilbert space corresponds to a representation of $SU(3)$.

Problem 9

Starting with the Minkowski version of the WZW action given in (171),

$$\mathcal{S}_{WZW} = -\frac{k}{8\pi} \int_{\Sigma} d^2x \operatorname{Tr}(\partial_i g \partial_i g^{-1}) + \frac{k}{12\pi} \int_{\mathcal{M}^3} \operatorname{Tr}(g^{-1} dg)^3 \quad (300)$$

rewrite this in terms of the lightcone coordinates u, v introduced earlier. Then for evolution along u , show that the canonical two-form is

$$\begin{aligned} \Omega_{ab}(v, v') &= \frac{k}{4\pi} \operatorname{Tr} \left[E_a(v) \partial_v \left(E_b(v) \delta(v - v') \right) - E_b(v) \partial_v \left(E_a(v) \delta(v - v') \right) \right. \\ &\quad \left. + [E_a(v), E_b(v')] \partial_v g g^{-1} \right] \end{aligned} \quad (301)$$

where E_a is matrix defined by $\delta g g^{-1} = E_a \delta \varphi^a$, $g = e^{-it^a \varphi^a}$. Define the current J_v by

$$J_v^a = \frac{k}{4\pi} (\partial_v g g^{-1})^a \quad (302)$$

Show that the Poisson brackets are given by

$$\{J_v(\theta), J_v(\varphi)\} = J_v(\theta \times \varphi) - \frac{k}{4\pi} \int \partial_v \theta^a \varphi^a \quad (303)$$

where θ_a and φ_a are arbitrary test functions, $(\theta \times \varphi)_a = f_{abc} \theta_b \varphi_c$.