

Path integrals for awkward actions

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Abstract

Time derivatives of scalar fields usually occur quadratically in the action. A simple Legendre transformation then turns the lagrangian into a hamiltonian that is quadratic in the momenta. The path integral over the momenta is gaussian. Mean values of operators are euclidian path integrals of their classical counterparts weighted by probability distributions. Monte Carlo simulations can estimate such mean values.

This familiar framework falls apart when the time derivatives do not occur quadratically. The Legendre transformation becomes difficult or so intractable that one can't find the hamiltonian. Even if one finds the hamiltonian, it typically is so complicated that one can't path-integrate over the momenta and get a euclidian path integral with a positive weight function. Monte Carlo simulations don't work when the weight function is not positive.

This paper solves both problems. It shows how to make path integrals without knowing the hamiltonian. It also shows how to estimate complex path integrals by combining the Monte Carlo method with numerical integration and parallel computation.

Since theories of scalar fields with quadratic time derivatives have infinite energy densities, this hybrid Monte Carlo method may lead to a theory with a finite (dark) energy density. It also may be useful for other sign problems.

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I. INTRODUCTION

Despite the success of renormalization, infinities remain a major problem in quantum field theory. This problem grows more important as cosmological observations continue to support the existence of dark energy [1], which may be the energy density of empty space. It would be nice to be able to compute finite energy densities in quantum field theory. This paper is meant to advance theories of scalar fields a step closer to that goal.

The ground-state energy of a theory is the low-temperature limit of the logarithmic derivative of the partition function $Z(\beta)$ with respect to the inverse temperature β , and so it is a ratio of euclidian path integrals. If the action density is quadratic in the time derivatives $\dot{\phi}$ of the fields, then a Legendre transformation gives a hamiltonian that is quadratic in the momenta π . One then can use the hamiltonian to write the partition function as a euclidian path integral in which the momentum integrals are gaussian. After one does the gaussian integrations, the partition function is a path integral of a probability distribution in the fields, and one can use Monte Carlo methods to estimate it.

This simple framework falls apart when the time derivatives do not occur quadratically. This collapse is unfortunate because theories that may have finite energy densities [2] have awkward actions that are not quadratic in the time derivatives of the fields, while those with quadratic time derivatives have infinite energy densities.

Legendre transformations work when the momenta are related to the fields and their derivatives by equations that are linear, quadratic, cubic, or quartic. But nonlinear Legendre transformations give hamiltonians that are complicated functions of the fields and their momenta, usually so complicated that path-integration over the momenta is hopeless. For such awkward actions, the exponential in the euclidian path integral for the partition function $Z(\beta)$

$$Z(\beta) = \text{Tr } e^{-\beta H} = \int \exp \left\{ \int_0^\beta \int [i \dot{\phi} \pi - H(\phi, \pi)] dt d^3x \right\} D\phi D\pi. \quad (1)$$

is complex. It is not a probability distribution, and the usual Monte Carlo methods do not work.

In most theories, however, the equations that relate the momenta to the fields and their derivatives are quintic or transcendental and have no known solutions. Such very awkward actions have inaccessible hamiltonians. To study the ground states of this wide class of

theories, we show in Sec. III how to write the partition function of such a theory as a path integral without knowledge of the hamiltonian. Our formula is a double path integral over the fields ϕ and over auxilliary time derivatives $\dot{\psi}$

$$Z(\beta) = \int \exp \left\{ \int_0^\beta \int \left[(i\dot{\phi}_\ell - \dot{\psi}_\ell) \frac{\partial L(\phi, \dot{\psi})}{\partial \dot{\psi}_\ell} + L(\phi, \dot{\psi}) \right] dt d^3x \right\} \left| \det \left(\frac{\partial^2 L(\phi, \dot{\psi})}{\partial \dot{\psi}_k \partial \dot{\psi}_\ell} \right) \right| D\phi D\dot{\psi}. \quad (2)$$

This path integral, like the one (1) for awkward actions, has a complex weight function that is not a probability distribution. Again the usual Monte Carlo methods do not work. Both path integrals are examples of the sign problem [3].

To estimate such complex path integrals, we introduce in Sec. **III ?** a hybrid method that combines Monte Carlo simulation with numerical integration. In theories with awkward actions, we numerically integrate over the momenta π in the double path integral (1). In theories with very awkward actions, we numerically integrate over the auxilliary time derivatives $\dot{\psi}$ in the double path integral (2). In both cases, we store the integrals in lookup tables. This solution to the sign problem is ideally suited to parallel computation and may be broadly useful. We demonstrate and test our hybrid method by applying it to a quantum-mechanical version of the Born-Infeld model [4] in Secs. VI & VII.

The paper does not discuss higher-derivative theories [5] or those in which some fields have no time derivatives [6].

II. REVIEW OF LEGENDRE TRANSFORMATIONS AND PATH INTEGRALS

The lagrangian of a theory tells us about symmetries and equations of motion, but one needs a hamiltonian to construct path integrals and to determine the time evolution of states and their energies. To find the hamiltonian of a theory of scalar fields $\phi = \{\phi_1, \dots, \phi_n\}$, one defines the conjugate momenta $\pi = \{\pi_1, \dots, \pi_n\}$ as the derivatives of the action density

$$\pi_j = \frac{\partial L}{\partial \dot{\phi}_j}, \quad (3)$$

and inverts these equations so as to write the time derivatives $\dot{\phi}_j = \dot{\phi}_j(\phi, \pi)$ of the fields in terms of the fields ϕ_ℓ and their momenta π_ℓ . The hamiltonian density then is

$$H = \sum_{j=1}^n \pi_j \dot{\phi}_j(\phi, \pi) - L(\phi, \dot{\phi}(\phi, \pi)). \quad (4)$$

When the action is quadratic in the time derivatives, Legendre's equations (3) are linear.

Once one has a hamiltonian, one inserts complete sets of eigenstates of the fields ϕ_j and their conjugate momenta π_j into the Boltzmann operator $\exp(-\beta H) = (\exp(-\beta H/n))^n$ and writes the partition function as the complex path integral

$$Z(\beta) = \text{Tr } e^{-\beta H} = \int \langle \phi | e^{-\beta H} | \phi \rangle D\phi = \int \exp \left\{ \int_0^\beta \int [i\dot{\phi}_j \pi_j - H(\phi, \pi)] dt d^3x \right\} D\phi D\pi. \quad (5)$$

If one can integrate over the momenta, then one gets the classic formula

$$Z(\beta) = \int \exp \left[\int_0^\beta \int -L_e(\phi, \dot{\phi}) dt d^3x \right] D\phi \quad (6)$$

in which L_e is the euclidian action density $D\phi$ is suitably redefined. In textbook theories, L_e is real and positive, and the exponential $\exp[-L_e(\phi, \dot{\phi})]$ is a probability distribution well-suited to Monte Carlo methods.

This procedure is straightforward when the action is quadratic in its time derivatives, and the integrals over the momenta are gaussian. But when the equations (3) that define the momenta have square roots, the hamiltonian also has a square root. When those equations are cubic or quartic, the Legendre transformation and the hamiltonian are much more complicated. When they are worse than quartic, no solution exists and the hamiltonian is inaccessible. We solve this problem in Sec. III.

III. PATH INTEGRALS FOR VERY AWKWARD ACTIONS

Our solution to the problem of making a path integral without a hamiltonian is to use functional integration to do Legendre's transformation by means of delta functionals that impose the relation (3) between momenta and the fields and their derivatives. Our formula for the partition function is a double path integral over the fields ϕ and over auxiliary time derivatives $\dot{\psi}$

$$Z(\beta) = \int \exp \left\{ \int_0^\beta \int \left[(i\dot{\phi}_\ell - \dot{\psi}_\ell) \frac{\partial L(\phi, \dot{\psi})}{\partial \dot{\psi}_\ell} + L(\phi, \dot{\psi}) \right] dt d^3x \right\} \left| \det \left(\frac{\partial^2 L(\phi, \dot{\psi})}{\partial \dot{\psi}_k \partial \dot{\psi}_\ell} \right) \right| D\phi D\dot{\psi} \quad (7)$$

in which the determinant converts $D\dot{\psi}$ into $D\pi$, and the energy density

$$E(\phi, \dot{\psi}) = \dot{\psi}_\ell \frac{\partial L(\phi, \dot{\psi})}{\partial \dot{\psi}_\ell} - L(\phi, \dot{\psi}) \quad (8)$$

is the hamiltonian density when the time derivatives $\dot{\psi}_\ell$ respect Legendre's relation (3). If the action is time independent, then the spatial integral of $E(\phi, \dot{\psi})$ is a constant when $\dot{\psi}_\ell = \dot{\phi}_\ell(\phi, \pi)$ and the equations of motion are obeyed.

The **double** integral (7) for the partition function $Z(\beta)$ is complex and ill-suited to estimation by Monte Carlo methods. We solve this problem in section V.

To derive our formula (7), we write the path integral (5) as

$$Z(\beta) = \int \exp \left\{ \int_0^\beta \int \left[i \dot{\phi}_j \pi_j - (\pi_k \dot{\psi}_k - L(\phi, \dot{\psi})) \right] dt d^3x \right\} \times \exp \left[i \int \left(\pi_\ell - \frac{\partial L}{\partial \dot{\psi}_\ell} \right) a_\ell d^4x \right] \left| \det \left(\frac{\partial^2 L}{\partial \dot{\psi}_k \partial \dot{\psi}_\ell} \right) \right| D\phi D\pi D\dot{\psi} Da \quad (9)$$

in which the integration over the n auxiliary fields a_ℓ makes the second exponential a delta functional $\delta(\pi - \partial L / \partial \dot{\psi})$ that enforces the definition (3) of the momentum π_j as the derivative of the action density L with respect to the time derivative $\dot{\phi}_j$. The jacobian is an $n \times n$ determinant that converts $D\dot{\psi}$ to $D\pi$. The integration is over all fields that are periodic with period β . Integrating first over a , we get

$$Z(\beta) = \int \exp \left\{ \int_0^\beta \int \left[i \dot{\phi}_j \pi_j - (\pi_k \dot{\psi}_k - L(\phi, \dot{\psi})) \right] dt d^3x \right\} \times \prod_{\ell=1}^n \left[\delta \left(\pi_\ell - \frac{\partial L}{\partial \dot{\psi}_\ell} \right) \right] \left| \det \left(\frac{\partial^2 L}{\partial \dot{\psi}_k \partial \dot{\psi}_\ell} \right) \right| D\phi D\pi D\dot{\psi}. \quad (10)$$

To integrate over the auxiliary time derivatives $\dot{\psi}$, we recall the delta-function rule that if a vector $g(x) = (g_1(x_1, \dots, x_n), \dots, g_n(x_1, \dots, x_n))$ is zero only at $x = x_0$, then

$$\int \delta^n(g_1(x_1, \dots, x_n), \dots, g_n(x_1, \dots, x_n)) \left| \det \left(\frac{\partial g_k(x)}{\partial x_\ell} \right) \right| d^n x = g(x_{10}, \dots, x_{n0}). \quad (11)$$

Thus integrating the **triple** path integral (10) over $\dot{\psi}$, we find that the delta functional and the jacobian require the time derivatives to assume values $\dot{\psi}_0(\phi, \pi) = \dot{\phi}(\phi, \pi)$ that satisfy the definition (3) of the momenta, and we get the path integral (5) over ϕ and π

$$Z(\beta) = \int \exp \left\{ \int_0^\beta \int \left[i \dot{\phi} \pi - (\pi \dot{\psi}_0(\phi, \pi) - L(\phi, \dot{\psi}_0(\phi, \pi))) \right] dt d^3x \right\} D\phi D\pi \\ = \int \exp \left\{ \int_0^\beta \int \left[i \dot{\phi}_j \pi_j - H(\phi, \pi) \right] dt d^3x \right\} D\phi D\pi. \quad (12)$$

On the other hand, if we integrate the triple path integral (10) over π , then we get our

proposed formula (7)

$$Z(\beta) = \int \exp \left\{ \int_0^\beta \int \left[(i\dot{\phi}_\ell - \dot{\psi}_\ell) \frac{\partial L(\phi, \dot{\psi})}{\partial \dot{\psi}_\ell} + L(\phi, \dot{\psi}) \right] dt d^3x \right\} \left| \det \left(\frac{\partial^2 L(\phi, \dot{\psi})}{\partial \dot{\psi}_k \partial \dot{\psi}_\ell} \right) \right| D\phi D\dot{\psi}. \quad (13)$$

This functional integral generalizes the path integral to theories of scalar fields in which **the** hamiltonian is unknown. A similar formula should work in theories of vector and tensor fields, apart from the issue of constraints.

Our first example is a free scalar field with action density

$$L = \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m^2 \phi^2. \quad (14)$$

The determinant in our formula (13) is unity because

$$\frac{\partial^2 L(\phi, \dot{\psi})}{\partial \dot{\psi}^2} = 1. \quad (15)$$

To simplify our notation, we will use the abbreviation

$$\int_0^\beta dt \int d^3x \equiv \int^\beta d^4x. \quad (16)$$

In this notation, the proposed path integral (13) for the free field theory (14) is

$$\begin{aligned} Z(\beta) &= \int \exp \left\{ \int^\beta \left[L(\phi, \dot{\psi}) + \dot{\psi}(i\dot{\phi} - \dot{\psi}) \right] d^4x \right\} D\phi D\dot{\psi} \\ &= \int \exp \left\{ \int^\beta \left[\frac{1}{2} \dot{\psi}^2 - \frac{1}{2} (\nabla \phi)^2 - \frac{1}{2} m^2 \phi^2 + \dot{\psi}(i\dot{\phi} - \dot{\psi}) \right] d^4x \right\} D\phi D\dot{\psi} \\ &= \int \exp \left\{ \int^\beta \left[-\frac{1}{2} (\dot{\psi} - i\dot{\phi})^2 - \frac{1}{2} \dot{\phi}^2 - \frac{1}{2} (\nabla \phi)^2 - \frac{1}{2} m^2 \phi^2 \right] d^4x \right\} D\phi D\dot{\psi} \\ &= \int \exp \left\{ \int^\beta \left[-\frac{1}{2} \dot{\phi}^2 - \frac{1}{2} (\nabla \phi)^2 - \frac{1}{2} m^2 \phi^2 \right] d^4x \right\} D\phi \\ &= \int \exp \left[- \int^\beta L_e(\phi, \dot{\phi}) d^4x \right] D\phi \end{aligned} \quad (17)$$

which is the standard result.

Our second example is the scalar Born-Infeld theory [4] with action density

$$L = M^4 \left(1 - \sqrt{1 - M^{-4} (\dot{\phi}^2 - (\nabla \phi)^2 - m^2 \phi^2)} \right) \quad (18)$$

and conjugate momentum

$$\pi = \frac{\partial L(\phi, \dot{\phi})}{\partial \dot{\phi}} = \frac{\dot{\phi}}{\sqrt{1 - M^{-4} (\dot{\phi}^2 - (\nabla \phi)^2 - m^2 \phi^2)}}. \quad (19)$$

The proposed path integral (13) is

$$Z(\beta) = \int \exp \left\{ \int^\beta \left[(i\dot{\phi} - \dot{\psi}) \frac{\partial L(\phi, \dot{\psi})}{\partial \dot{\psi}} + L(\phi, \dot{\psi}) \right] d^4x \right\} \left| \frac{\partial^2 L(\phi, \dot{\psi})}{\partial \dot{\psi}^2} \right| D\phi D\dot{\psi} \quad (20)$$

in which

$$\frac{\partial L(\phi, \dot{\psi})}{\partial \dot{\psi}} = \frac{\dot{\psi}}{\sqrt{1 - M^{-4} (\dot{\psi}^2 - (\nabla \phi)^2 - m^2 \phi^2)}} \quad (21)$$

and

$$\frac{\partial^2 L(\phi, \dot{\psi})}{\partial \dot{\psi}^2} = \frac{1 + M^{-4} ((\nabla \phi)^2 + m^2 \phi^2)}{\left[1 - M^{-4} (\dot{\psi}^2 - (\nabla \phi)^2 - m^2 \phi^2) \right]^{3/2}}. \quad (22)$$

Substituting these formulas into (20) gives

$$\begin{aligned} Z(\beta) = \int \exp \left\{ \int^\beta \left[\frac{(i\dot{\phi} - \dot{\psi})\dot{\psi}}{\sqrt{1 - M^{-4} (\dot{\psi}^2 - (\nabla \phi)^2 - m^2 \phi^2)}} \right. \right. \\ \left. \left. + M^4 \left(1 - \sqrt{1 - M^{-4} (\dot{\psi}^2 - (\nabla \phi)^2 - m^2 \phi^2)} \right) \right] d^4x \right\} \\ \times \frac{1 + M^{-4} ((\nabla \phi)^2 + m^2 \phi^2)}{\left[1 - M^{-4} (\dot{\psi}^2 - (\nabla \phi)^2 - m^2 \phi^2) \right]^{3/2}} D\phi D\dot{\psi}. \end{aligned} \quad (23)$$

We can set

$$\pi = \frac{\partial L(\phi, \dot{\psi})}{\partial \dot{\psi}} = \frac{\dot{\psi}}{\sqrt{1 - M^{-4} (\dot{\psi}^2 - (\nabla \phi)^2 - m^2 \phi^2)}} \quad (24)$$

and so absorb the jacobian in

$$d\pi = \frac{\partial \pi}{\partial \dot{\psi}} d\dot{\psi} = \frac{\partial^2 L(\phi, \dot{\psi})}{\partial \dot{\psi}^2} d\dot{\psi} = \frac{1 + M^{-4} ((\nabla \phi)^2 + m^2 \phi^2)}{\left[1 - M^{-4} (\dot{\psi}^2 - (\nabla \phi)^2 - m^2 \phi^2) \right]^{3/2}} d\dot{\psi}. \quad (25)$$

The partition function (23) then is

$$Z(\beta) = \int \exp \left[\int^\beta (i\dot{\phi} - \dot{\psi})\pi + M^4 \left(1 - \sqrt{1 - (\dot{\psi}^2 - (\nabla \phi)^2 - m^2 \phi^2) / M^4} \right) d^4x \right] D\phi D\pi \quad (26)$$

where now $\dot{\psi}(\phi, \pi)$ is the function of ϕ and π defined by (24).

This theory is one of the few in which we can solve Legendre's equation (24) for the time derivative $\dot{\psi}$

$$\dot{\psi} = \frac{\pi}{\sqrt{1 + M^{-4} \pi^2}} \sqrt{1 + M^{-4} ((\nabla \phi)^2 + m^2 \phi^2)} \quad (27)$$

and find as the hamiltonian density

$$\begin{aligned} H(\phi, \pi) &= \pi \dot{\psi} - L(\phi, \dot{\psi}) \\ &= \frac{\pi^2 \sqrt{1 + M^{-4} ((\nabla \phi)^2 + m^2 \phi^2)}}{\sqrt{1 + M^{-4} \pi^2}} - M^4 \\ &\quad + M^4 \sqrt{1 - M^{-4} \left(\frac{\pi^2 (1 + M^{-4} ((\nabla \phi)^2 + m^2 \phi^2))}{1 + M^{-4} \pi^2} - (\nabla \phi)^2 - m^2 \phi^2 \right)} \\ &= \frac{\pi^2 \sqrt{M^4 + (\nabla \phi)^2 + m^2 \phi^2}}{\sqrt{M^4 + \pi^2}} + M^4 \frac{\sqrt{M^4 + (\nabla \phi)^2 + m^2 \phi^2}}{\sqrt{M^4 + \pi^2}} - M^4 \\ &= \sqrt{(M^4 + \pi^2) (M^4 + (\nabla \phi)^2 + m^2 \phi^2)} - M^4. \end{aligned} \quad (28)$$

Thus for this theory, the double path integral (1) is

$$Z(\beta) = \int \exp \left\{ \int^\beta \left[i \dot{\phi} \pi - \sqrt{(M^4 + \pi^2) (M^4 + (\nabla \phi)^2 + m^2 \phi^2)} + M^4 \right] d^4 x \right\} D\phi D\pi. \quad (29)$$

Our third example is the theory defined by the action density

$$L = M^4 \exp(L_0/M^4) \quad (30)$$

in which L_0 is the action density (14) of the free field. The derivatives of L are

$$\frac{\partial L}{\partial \dot{\psi}} = M^{-4} \dot{\psi} L \quad \text{and} \quad \frac{\partial^2 L}{\partial \dot{\psi}^2} = M^{-4} (1 + M^{-4} \dot{\psi}^2) L. \quad (31)$$

So the proposed path integral is

$$\begin{aligned} Z(\beta) &= \int \exp \left\{ \int^\beta \left[L(\phi, \dot{\psi}) + \frac{\partial L(\phi, \dot{\psi})}{\partial \dot{\psi}} (i \dot{\phi} - \dot{\psi}) \right] d^4 x \right\} \left| \frac{\partial^2 L(\phi, \dot{\psi})}{\partial \dot{\psi}^2} \right| D\phi D\dot{\psi} \\ &= \int \exp \left\{ \int^\beta \left[1 + \frac{\dot{\psi} (i \dot{\phi} - \dot{\psi})}{M^4} \right] L(\phi, \dot{\psi}) d^4 x \right\} M^{-4} (1 + M^{-4} \dot{\psi}^2) L D\phi D\dot{\psi}. \end{aligned} \quad (32)$$

Our fourth example is the Nambu-Gotō action density

$$L = -\frac{T_0}{c} \int_0^{\sigma_1} \sqrt{\left(\dot{X} \cdot X' \right)^2 - \left(\dot{X} \right)^2 \left(X' \right)^2} \quad (33)$$

in which the tau or time derivatives of the coordinate fields X^μ do not occur quadratically [7].

The momenta are

$$\mathcal{P}_\mu^\tau = \frac{\partial L}{\partial \dot{X}^\mu} = -\frac{T_0}{c} \frac{(\dot{X} \cdot X')X'_\mu - (X')^2 \dot{X}_\mu}{\sqrt{(\dot{X} \cdot X')^2 - (\dot{X})^2 (X')^2}} \quad (34)$$

and the second derivatives of the Lagrange density are

$$\begin{aligned} \frac{\partial^2 L}{\partial \dot{X}^\mu \partial \dot{X}^\nu} = \frac{T_0}{c} & \left[\frac{\delta_{\mu\nu} X'^2 - X'_\mu X'_\nu}{\sqrt{(\dot{X} \cdot X')^2 - (\dot{X})^2 (X')^2}} \right. \\ & \left. - \frac{\left((\dot{X} \cdot X')X'_\mu - (X')^2 \dot{X}_\mu \right) \left((\dot{X} \cdot X')X'_\nu - (X')^2 \dot{X}_\nu \right)}{\left[(\dot{X} \cdot X')^2 - (\dot{X})^2 (X')^2 \right]^{3/2}} \right]. \end{aligned} \quad (35)$$

The proposed partition function (13) for the Nambu-Gotō action is then

$$Z(\beta) = \int \exp \left\{ \int^\beta \left[(i\dot{X}^\mu - \dot{Y}^\mu) \frac{\partial L(X, \dot{Y})}{\partial \dot{Y}^\mu} + L(X, \dot{Y}) \right] d^4 x \right\} \left| \det \left[\frac{\partial^2 L(X, \dot{Y})}{\partial \dot{Y}^\mu \partial \dot{Y}^\nu} \right] \right| DX D\dot{Y} \quad (36)$$

in which the formulas (34) and (35) (with $\dot{X}^\mu \rightarrow \dot{Y}^\mu$) are to be substituted for the first and second derivatives of the action density L with respect to the tau derivatives \dot{Y}^μ .

IV. RATIOS OF COMPLEX MONTE CARLOS ARE UNRELIABLE

The mean value of an observable $A[\phi]$ at inverse temperature β is

$$\begin{aligned} \langle A[\phi] \rangle &= \frac{\text{Tr } A[\phi] e^{-\beta H}}{\text{Tr } e^{-\beta H}} \\ &= \int A[\phi] \exp \left[\int \left(i\dot{\phi}_j - \dot{\psi}_j \right) \frac{\partial L}{\partial \dot{\psi}_j} + L(\phi, \dot{\psi}) d^4 x \right] \left| \det \left(\frac{\partial^2 L}{\partial \dot{\psi}_k \partial \dot{\psi}_\ell} \right) \right| D\phi D\dot{\psi} \\ &\quad \Bigg/ \int \exp \left[\int \left(i\dot{\phi}_j - \dot{\psi}_j \right) \frac{\partial L}{\partial \dot{\psi}_j} + L(\phi, \dot{\psi}) d^4 x \right] \left| \det \left(\frac{\partial^2 L}{\partial \dot{\psi}_k \partial \dot{\psi}_\ell} \right) \right| D\phi D\dot{\psi}. \end{aligned} \quad (37)$$

The complex action

$$S = \int \left(i\dot{\phi}_j - \dot{\psi}_j \right) \frac{\partial L}{\partial \dot{\psi}_j} + L(\phi, \dot{\psi}) d^4 x \quad (38)$$

oscillates and does not give us a probability distribution unless we can integrate over $D\dot{\psi}$. One can write the mean value (37) as a ratio of mean values

$$\begin{aligned}\langle A[\phi] \rangle &= \left\langle A[\phi] \exp \left[\int i \dot{\phi}_j \frac{\partial L}{\partial \dot{\psi}_j} d^4x \right] \right\rangle / \left\langle \exp \left[\int i \dot{\phi}_j \frac{\partial L}{\partial \dot{\psi}_j} d^4x \right] \right\rangle \\ &= \int A[\phi] \exp \left[\int i \dot{\phi}_j \frac{\partial L}{\partial \dot{\psi}_j} d^4x \right] P(\phi, \dot{\psi}) D\phi D\dot{\psi} \\ &\quad / \int \exp \left[\int i \dot{\phi}_j \frac{\partial L}{\partial \dot{\psi}_j} d^4x \right] P(\phi, \dot{\psi}) D\phi D\dot{\psi}\end{aligned}\tag{39}$$

in which the functional $P(\phi, \dot{\psi})$ is a normalized probability distribution

$$\begin{aligned}P(\phi, \dot{\psi}) &= \exp \left[\int \left(L(\phi, \dot{\psi}) - \dot{\psi}_j \frac{\partial L}{\partial \dot{\psi}_j} \right) d^4x \right] \left| \det \left(\frac{\partial^2 L}{\partial \dot{\psi}_k \partial \dot{\psi}_\ell} \right) \right| \\ &\quad / \int \exp \left[\int \left(L(\phi, \dot{\psi}) - \dot{\psi}_j \frac{\partial L}{\partial \dot{\psi}_j} \right) d^4x \right] \left| \det \left(\frac{\partial^2 L}{\partial \dot{\psi}_k \partial \dot{\psi}_\ell} \right) \right| D\phi D\dot{\psi}.\end{aligned}\tag{40}$$

Although in principle one can use the Monte Carlo method [8] to estimate the numerator N and the denominator D of the ratio (39), both N and D are the mean values of complex oscillating functionals. In many if not most cases of interest, both N and D are smaller than the measurement errors δN and δD in computations of reasonable lengths. The error in the observable $A[\phi]$ is

$$\delta \langle A[\phi] \rangle = \delta \frac{N}{D} = \frac{\delta N}{D} - \frac{N}{D^2} \delta D = \frac{\delta N}{D} - \langle A[\phi] \rangle \frac{\delta D}{D},\tag{41}$$

and in many cases both N and D are zero in the limit in which $\beta \rightarrow \infty$.

For instance, suppose we apply the technique (39–40) to the computation of the ground-state energy $\langle H \rangle = N/D$ of the harmonic oscillator in which the numerator is

$$\begin{aligned}N &= \int \left(\frac{p^2}{2m} + \frac{1}{2} m \omega^2 q^2 \right) \exp \left[\int \left(i \dot{q} p - \frac{p^2}{2m} - \frac{1}{2} m \omega^2 q^2 \right) dt \right] Dp Dq \\ &\quad / \int \exp \left[\int \left(-\frac{p^2}{2m} - \frac{1}{2} m \omega^2 q^2 \right) dt \right] Dp Dq,\end{aligned}\tag{42}$$

the denominator D is

$$\begin{aligned}D &= \int \exp \left[\int \left(i \dot{q} p - \frac{p^2}{2m} - \frac{1}{2} m \omega^2 q^2 \right) dt \right] Dp Dq \\ &\quad / \int \exp \left[\int \left(-\frac{p^2}{2m} - \frac{1}{2} m \omega^2 q^2 \right) dt \right] Dp Dq,\end{aligned}\tag{43}$$

and the measure $DpDq$ is

$$DpDq = \prod_{j=1}^n \frac{1}{2\pi} dp_j dq_j. \quad (44)$$

In the continuum limit ($n \rightarrow \infty$, $dt \rightarrow 0$, with $\beta = n dt$ fixed), the numerator \mathcal{N} of the denominator $D \equiv \mathcal{N}/\mathcal{D}$ of the ratio N/D is the partition function

$$\begin{aligned} \mathcal{N} &= Z(\beta) = \text{Tr } e^{-\beta H} \\ &= \int \exp \left[\int \left(i\dot{q}p - \frac{p^2}{2m} - \frac{1}{2}m\omega^2 q^2 \right) dt \right] DpDq \\ &= \frac{1}{2 \sinh(\beta\omega/2)}, \end{aligned} \quad (45)$$

and the denominator is

$$\begin{aligned} \mathcal{D} &= \int \exp \left[\int \left(-\frac{p^2}{2m} - \frac{1}{2}m\omega^2 q^2 \right) dt \right] DpDq \\ &= \prod_{j=1}^n \int \frac{dp_j dq_j}{2\pi} \exp \left[\sum_{j=1}^n \left(-\frac{p_j^2}{2m} - \frac{1}{2}m\omega^2 q_j^2 \right) \frac{\beta}{n} \right] \\ &= \left(\frac{1}{2\pi} \right)^n \left(\frac{2\pi mn}{\beta} \right)^{n/2} \prod_{j=1}^n \int dq_j \exp \left[\sum_{j=1}^n \left(-\frac{1}{2}m\omega^2 q_j^2 \right) \frac{\beta}{n} \right] \\ &= \left(\frac{1}{2\pi} \right)^n \left(\frac{2\pi mn}{\beta} \right)^{n/2} \left(\frac{2\pi n}{m\omega^2 \beta} \right)^{n/2} = \left(\frac{n}{\beta\omega} \right)^n. \end{aligned} \quad (46)$$

This denominator goes to infinity as $n \rightarrow \infty$ and $\beta/n \rightarrow 0$ for any $\beta \neq 0$. So the denominator D vanishes

$$D = \frac{1}{2 \sinh(\beta\omega/2) \mathcal{D}} = 0. \quad (47)$$

The numerator also vanishes, so the ratio $\langle H \rangle = N/D$ is hard to estimate, being $0/0$.

In general, the double-ratio method (39–40) is not a reliable way to estimate the mean value of an observable (37).

V. HYBRID MONTE CARLOS

Monte Carlos let us estimate the mean values of observables weighted by probability distributions [8]. They fail when the weight function assumes negative or complex values. This failure is one aspect of the sign problem [3]. The double-ratio trick (39–40) is unreliable.

These problems are not hopeless however. For although the weight functions of the double path integrals (1) and (2) are complex, the integrals of these complex weight functions over

the momenta π or over the auxiliary time derivatives $\dot{\psi}$ are real and positive. They are the probability distribution that determines the partition function and the mean values of various observables.

Although one can't do these integrals analytically, one can do them numerically. These numerical integrations are perfectly suited to parallel computation. Our hybrid method of computing the partition functions of theories with awkward and very awkward actions is to use parallel computation to numerically integrate over the momenta π or over the auxiliary time derivatives $\dot{\psi}$ in the double path integrals (1) and (2) and to store these integrals in look-up tables. We then use the Monte Carlo method guided by the stored probability distribution to estimate the partition function.

Although our main goal is to use this hybrid method to study the ground states of field theories, we will for simplicity explain and test it in the context of quantum mechanics in this paper and then demonstrate and test it.

Suppose that we know the hamiltonian $H(q, p)$ but can't integrate over the momentum p analytically. Then the partition function $Z(\beta)$ is

$$\begin{aligned} Z(\beta) &= \text{Tr } e^{-\beta H} = \int \exp \left\{ \int_0^\beta [i\dot{q}p - H(q, p)] dt \right\} Dp Dq \\ &= \prod_{j=1}^n \int \frac{dp_j dq_j}{2\pi} \exp \left[\sum_{\ell=0}^{\beta/a} i(q_{\ell+1} - q_\ell)p_\ell - aH(q_\ell, p_\ell) \right]. \end{aligned} \quad (48)$$

We know that

$$P[q, \beta] = \int \exp \left\{ \int_0^\beta [i\dot{q}p - H(q, p)] dt \right\} Dp \quad (49)$$

is a functional probability distribution that assigns a number $P[q, \beta]$ to every path $q(t)$. It is the limit as $n \rightarrow \infty$ and $a = \beta/n \rightarrow 0$ of the multiple integral

$$P_n[q, \beta] = \prod_{j=1}^n \int \frac{dp_j}{\sqrt{2\pi}} \exp \left[\sum_{\ell=0}^n i(q_{\ell+1} - q_\ell)p_\ell - aH(q_\ell, p_\ell) \right]. \quad (50)$$

If the hamiltonian is even in the momentum, then the probability distribution is real

$$P_n[q, \beta] = \prod_{j=1}^n \int \frac{dp_j}{\sqrt{2\pi}} \prod_{k=1}^n \cos((q_{k+1} - q_k)p_k) e^{-aH(q_k, p_k)}. \quad (51)$$

The partition function $Z(\beta)$ is

$$Z(\beta) = \int P[q, \beta] Dq = \int \prod_{j=1}^n \frac{dq_j}{\sqrt{2\pi}} P_n[q, \beta]. \quad (52)$$

The mean value of the energy at inverse temperature β is

$$\langle H \rangle_\beta = \frac{\text{Tr } H e^{-\beta H}}{\text{Tr } e^{-\beta H}} = - \frac{1}{Z(\beta)} \frac{dZ(\beta)}{d\beta} = - \frac{1}{Z(\beta)} \int \prod_{j=1}^n \frac{dq_j}{\sqrt{2\pi}} \frac{dP_n[q, \beta]}{d\beta}. \quad (53)$$

The derivative of the probability distribution with respect to $\beta = n a$ is

$$- \frac{dP_n[q, \beta]}{d\beta} = \frac{1}{n} \sum_{k=1}^n \int \prod_{j=1}^n \frac{dp_j}{\sqrt{2\pi}} H(q_k, p_k) \exp \left[\sum_{\ell=0}^n i(q_{j+1} - q_j) p_j - a H(q_\ell, p_\ell) \right]. \quad (54)$$

So the mean value of the hamiltonian at inverse temperature β is

$$\begin{aligned} \langle H \rangle_\beta &= \frac{1}{n} \sum_{k=1}^n \int \prod_{j=1}^n dq_j dp_j H(q_k, p_k) \exp \left[\sum_{\ell=0}^n i(q_{j+1} - q_j) p_j - a H(q_\ell, p_\ell) \right] \\ &\quad \Bigg/ \int \prod_{j=1}^n dq_j dp_j \exp \left[\sum_{\ell=0}^n i(q_{\ell+1} - q_\ell) p_\ell - a H(q_\ell, p_\ell) \right]. \end{aligned} \quad (55)$$

We do the p integrations numerically, setting

$$A(q_{\ell+1}, q_\ell) = \langle q_{\ell+1} | e^{-aH(q_\ell, p)} | q_\ell \rangle = \int_{-\infty}^{\infty} \frac{dp}{\sqrt{2\pi}} \exp [i(q_{\ell+1} - q_\ell)p - a H(q_\ell, p)]. \quad (56)$$

and

$$C(q_{\ell+1}, q_\ell) = \int_{-\infty}^{\infty} \frac{dp}{\sqrt{2\pi}} H(q_\ell, p) \exp [i(q_{\ell+1} - q_\ell)p - a H(q_\ell, p)]. \quad (57)$$

In terms of these numerical integrals, the mean value of the hamiltonian is

$$\langle H \rangle_\beta = \frac{1}{n} \sum_{k=1}^n \int dq_k \prod_{j=1, j \neq k}^n dq_j C(q_{k+1}, q_k) A(q_{j+1}, q_j) \Bigg/ \int \prod_{j=1}^n dq_j A(q_{j+1}, q_j) \quad (58)$$

which we may write as

$$\langle H \rangle_\beta = \frac{1}{n} \sum_{k=1}^n \int \prod_{j=1}^n dq_j \frac{C(q_{k+1}, q_k)}{A(q_{k+1}, q_k)} A(q_{j+1}, q_j) \Bigg/ \int \prod_{j=1}^n dq_j A(q_{j+1}, q_j). \quad (59)$$

We do a **Monte Carlo** over the probability distribution

$$P(q) = \prod_{j=1}^n A(q_{j+1}, q_j) \Bigg/ \int \prod_{j=1}^n dq_j A(q_{j+1}, q_j) \quad (60)$$

and measure the ratio

$$\langle H \rangle_\beta = \left\langle \frac{1}{n} \sum_{k=1}^n \frac{C(q_{k+1}, q_k)}{A(q_{k+1}, q_k)} \right\rangle = \int \frac{1}{n} \sum_{k=1}^n \frac{C(q_{k+1}, q_k)}{A(q_{k+1}, q_k)} P(q) Dq. \quad (61)$$

The probability distribution $P[q, \beta]$ is positive. For instance, the quantity

$$\langle q^2(t) \rangle = \text{Tr} e^{-(\beta-t)H} q^2 e^{-tH} = \int q^2(t) P[q, \beta] Dq \quad (62)$$

is positive for every t and every path $q(t)$. In most problems of interest, the hamiltonian is an even function of the momentum, $H(q, -p) = H(q, p)$, and the integrals (56 & 57) are real

$$\begin{aligned} A(q_{\ell+1}, q_{\ell}) &= \sqrt{\frac{2}{\pi}} \int_0^{\infty} dp \cos[(q_{\ell+1} - q_{\ell})p] e^{-a H(q_{\ell}, p)} \\ C(q_{\ell+1}, q_{\ell}) &= \sqrt{\frac{2}{\pi}} \int_0^{\infty} dp H(q_{\ell}, p) \cos[(q_{\ell+1} - q_{\ell})p] e^{-a H(q_{\ell}, p)}. \end{aligned} \quad (63)$$

We use these explicitly real forms in our Monte Carlos.

In most problems of interest, the hamiltonian increases monotonically with the momentum when the momentum is positive

$$\frac{\partial H(q, p)}{\partial p} > 0 \quad \text{when} \quad p > 0 \quad (64)$$

and so the exponential $\exp[-a H(q_{\ell}, p)]$ in the integral (63) decreases monotonically with p for $p > 0$

$$\frac{\partial}{\partial p} e^{-a H(q_{\ell}, p)} = -a \frac{\partial H(q, p)}{\partial p} e^{-a H(q_{\ell}, p)} < 0 \quad \text{for} \quad p > 0. \quad (65)$$

Now let us  the domain of the integration (63) into the successive intervals

$$I_n = \left[\frac{n\pi}{2|q_{\ell+1} - q_{\ell}|}, \frac{(n+1)\pi}{2|q_{\ell+1} - q_{\ell}|} \right] \quad (66)$$

for $n = 0, 1, \dots$. Because the exponential decreases monotonically with p , it follows that the integral over any pair of intervals $I_{4n} \cup I_{4n+1}$ for $n \geq 0$ is positive. Invoking the inequality (65) once again, we see that the integral over any quartet of intervals $I_{4n} \cup I_{4n+1} \cup I_{4n+2} \cup I_{4n+3}$ for $n \geq 0$ also is positive. Thus the integral (56) is positive as long as the hamiltonian is a monotonically increasing, even function of the momentum.

For instance, when H represents a harmonic oscillator

$$H = \frac{p^2}{2m} + \frac{m\omega^2 q^2}{2}, \quad (67)$$

the integral (56) is obviously positive

$$A(q_{\ell+1}, q_{\ell}) = \sqrt{\frac{m}{a}} \exp \left\{ -a \left[\frac{m(q_{\ell+1} - q_{\ell})^2}{2a^2} + \frac{m\omega^2 q_{\ell}^2}{2} \right] \right\}. \quad (68)$$

To take a Metropolis step, we pick a new q'_j and look up the value of the probability distribution

$$P(q'_j) = A(q_{j+1}, q'_j) A(q'_j, q_{j-1}) \quad (69)$$

If $P(q'_j) \geq P(q_j)$, then we accept the new q'_j . If $P(q'_j) < P(q_j)$, then we accept the new q'_j with probability

$$P(q_j \rightarrow q'_j) = P(q'_j)/P(q_j). \quad (70)$$

VI. APPLICATION OF THE HYBRID METHOD TO THE BORN-INFELD OSCILLATOR

In this section we demonstrate and test our hybrid model on a theory with an awkward action, the quantum-mechanical version of the scalar Born-Infeld model (18–29). The lagrangian of this model is

$$L = Mc^2 - Mc^2 \left[1 - \frac{m}{Mc^2} (\dot{q}^2 - \omega^2 q^2) \right]^{1/2}. \quad (71)$$

The momentum is

$$p = \frac{m\dot{q}}{\sqrt{1 - m(\dot{q}^2 - \omega^2 q^2)/(Mc^2)}}, \quad (72)$$

and the velocity is

$$\dot{q} = \frac{p}{m} \frac{\sqrt{1 + m\omega^2 q^2/Mc^2}}{\sqrt{1 + p^2/(mMc^2)}}. \quad (73)$$

The hamiltonian of the Born-Infeld oscillator is

$$H = \sqrt{(p^2/m + Mc^2)(Mc^2 + m\omega^2 q^2)} - Mc^2. \quad (74)$$

In terms of the hamiltonian $H_0 = p^2/2m + m\omega^2 q^2/2$ of the harmonic oscillator, the hamiltonian H of the Born-Infeld oscillator in the limit $M/m \gg 1$ is

$$H = H_0 - \frac{1}{8Mc^2} \left(\frac{p^2}{2m} - \frac{m\omega^2 q^2}{2} \right)^2 \left(1 - \frac{H_0}{Mc^2} \right) + \dots \quad (75)$$

and

$$H = \sqrt{Mc^2 m \omega^2 q^2} \left[1 + \frac{p^2}{2mMc^2} - \frac{p^4}{8(mMc^2)^2} \right] \left[1 + \frac{Mc^2}{2m\omega^2 q^2} - \frac{(Mc^2)^2}{32(m\omega^2 q^2)^2} \right] + \dots \quad (76)$$

for $M/m \ll 1$. The energy levels of the Born-Infeld oscillator, like those of the harmonic oscillator, are independent of the mass m due to a symmetry that the change of variables to $q' = q\sqrt{m}$ and $p' = p/\sqrt{m}$ reveals.

With $c = 1$ and $\beta = na$, the partition function is

$$\begin{aligned}
Z(\beta) &= \text{Tr } e^{-\beta H} = \int \exp \left\{ \int_0^\beta [i\dot{q}p - H(q, p)] dt \right\} Dp Dq \\
&= \prod_{j=1}^n \int \frac{dp_j dq_j}{2\pi} \exp \left[\sum_{\ell=0}^n i(q_{\ell+1} - q_\ell) p_\ell - a H(q_\ell, p_\ell) \right] \\
&= \prod_{j=1}^n \int \frac{dp_j dq_j}{2\pi} \exp \left[\sum_{\ell=0}^n i(q_{\ell+1} - q_\ell) p_\ell - a \left(\sqrt{p_\ell^2/m + M} \sqrt{M + m\omega^2 q_\ell^2} - M \right) \right].
\end{aligned} \tag{77}$$

In terms of the variables to $q' = q\sqrt{m}$ and $p' = p/\sqrt{m}$, which satisfy the commutation relation $[q', p'] = i$, the Born-Infeld hamiltonian (74) is

$$H = \sqrt{(p'^2 + M) (M + \omega^2 q'^2)} - M, \tag{78}$$

which shows that the energy levels are independent of the mass parameter m . To simplify our notation and expose the actual dependence of these energies, we change variables again to $p' = \sqrt{M}p''$ and $q' = \sqrt{M}q''/\omega$. Now the hamiltonian is

$$H = M \left[\sqrt{(p''^2 + 1) (q''^2 + 1)} - 1 \right], \tag{79}$$

and with $a' = aM$ the partition function is

$$Z(\beta) = \prod_{j=1}^n \int \frac{M dp_j'' dq_j''}{2\pi\omega} \exp \left\{ \sum_{\ell=0}^n \left[i \frac{M}{\omega} (q_{\ell+1}'' - q_\ell'') p_\ell'' - a' \left(\sqrt{(p_\ell''^2 + 1) (q_\ell''^2 + 1)} - 1 \right) \right] \right\}. \tag{80}$$

The mean value of the hamiltonian at inverse temperature $\beta = na = na'/M$ is

$$\langle H \rangle_\beta = - \frac{\text{Tr } H e^{-\beta H}}{\text{Tr } e^{-\beta H}} = - \frac{1}{Z(\beta)} \frac{dZ(\beta)}{d\beta} = - \frac{1}{n Z(\beta)} \frac{dZ(\beta)}{da} = - \frac{M}{n Z(\beta)} \frac{dZ(\beta)}{da'}. \tag{81}$$

Dropping all the primes, we see that the energy $\langle H \rangle_\beta$ is a function of the ratio M/ω and is proportional to M

$$\begin{aligned}
\langle H \rangle_\beta &= \prod_{j=1}^n \int dp_j dq_j \left[\frac{M}{n} \sum_{\ell=0}^n \left(\sqrt{(p_\ell^2 + 1) (q_\ell^2 + 1)} - 1 \right) \right] \\
&\quad \times \exp \left[\sum_{\ell=0}^n i \frac{M}{\omega} (q_{\ell+1} - q_\ell) p_\ell - a \left(\sqrt{(p_\ell^2 + 1) (q_\ell^2 + 1)} - 1 \right) \right] \\
&\quad \Big/ \prod_{j=1}^n \int dp_j dq_j \exp \left[\sum_{\ell=0}^n i \frac{M}{\omega} (q_{\ell+1} - q_\ell) p_\ell - a \left(\sqrt{(p_\ell^2 + 1) (q_\ell^2 + 1)} - 1 \right) \right].
\end{aligned} \tag{82}$$

The ground-state energy is the limit of the ratio as $\beta \rightarrow \infty$ and $a \rightarrow 0$.

We wrote Fortran90 codes to compute in parallel the momentum integrals

$$A(q_{\ell+1}, q_{\ell}) = \int_0^{\infty} dp \cos \left[\frac{M}{\omega} (q_{\ell+1} - q_{\ell}) p \right] \exp \left[-a \left(\sqrt{(p^2 + 1)(q_{\ell}^2 + 1)} - 1 \right) \right] \quad (83)$$

and

$$C(q_{\ell+1}, q_{\ell}) = M \int_0^{\infty} dp \left(\sqrt{(p^2 + 1)(q_{\ell}^2 + 1)} - 1 \right) \times \cos \left[\frac{M}{\omega} (q_{\ell+1} - q_{\ell}) p \right] \exp \left[-a \left(\sqrt{(p^2 + 1)(q_{\ell}^2 + 1)} - 1 \right) \right] \quad (84)$$

for suitably large sets of values of q_{ℓ} and $q_{\ell+1}$ and stored them in look-up tables. We then used the look-up tables in a generic Monte Carlo with the Metropolis step (69–70) to estimate the mean value of the hamiltonian at inverse temperature β

$$\langle H \rangle_{\beta} = \left\langle \frac{1}{n} \sum_{k=1}^n \frac{C(q_{k+1}, q_k)}{A(q_{k+1}, q_k)} \right\rangle = \int \frac{1}{n} \sum_{k=1}^n \frac{C(q_{k+1}, q_k)}{A(q_{k+1}, q_k)} P_n[q, \beta] Dq \quad (85)$$

in which the un-normalized probability distribution is

$$P_n(q, \beta) = \prod_{\ell=1}^n A(q_{\ell+1}, q_{\ell}) \quad (86)$$

and $q_{n+1} \equiv q_1$.

The Monte Carlo codes ran fast; all the work is in the look-up tables. We made look-up tables for $0.1 \leq Mc^2/(\hbar\omega) \leq 10$. We plotted our hybrid Monte Carlo (83–85) estimates of the ground-state energy of the Born-Infeld oscillator as blue dots in Fig. 1 and listed them in Table I. The statistical errors are smaller than the dots.

To test these results, we used Matlab to compute the exact eigenvalues of the Born-Infeld oscillator. In terms of the harmonic-oscillator variables

$$a = \sqrt{\frac{m\omega}{2}} \left(q + \frac{ip}{m\omega} \right) \quad \text{and} \quad a^{\dagger} = \sqrt{\frac{m\omega}{2}} \left(q - \frac{ip}{m\omega} \right), \quad (87)$$

the operators q and p are $q = (a^{\dagger} + a)/\sqrt{2m\omega}$ and $p = i\sqrt{m\omega/2}(a^{\dagger} - a)$, and so the hamiltonian (74) is

$$H = \sqrt{Mc^2 - \frac{\omega}{2}(a^{\dagger} - a)^2} \sqrt{Mc^2 + \frac{\omega}{2}(a^{\dagger} + a)^2} - Mc^2 \quad (88)$$

which affirms that like the hamiltonian of the simple harmonic oscillator, it is independent of the mass m . We made a 1000×1000 matrix a as $\text{diag}(\text{sqrt}([1:N_{\text{max}}]), 1)$ with N_{max}

$= 1000$ and a^\dagger as its transpose. The Matlab command `eig(sqrtm(H))` then gave the exact energy eigenvalues, which generated the red curves in the figures and the exact results in the tables.

TABLE I: Exact (Matlab) and hybrid Monte Carlo results (83–85) for the ground-state energy $E_0/(\hbar\omega)$ of the Born-Infeld hamiltonian (74) for $0.1 \leq Mc^2/(\hbar\omega) \leq 10$.

$Mc^2/(\hbar\omega)$	$E_0/(\hbar\omega)$ exact	$E_0/(\hbar\omega)$ Monte Carlo
0.1	0.1881	0.1759
0.5	0.3155	0.3191
1.0	0.3702	0.3746
2.5	0.4288	0.4308
5.0	0.4587	0.4603
7.5	0.4708	0.4723
10.0	0.4774	0.4781

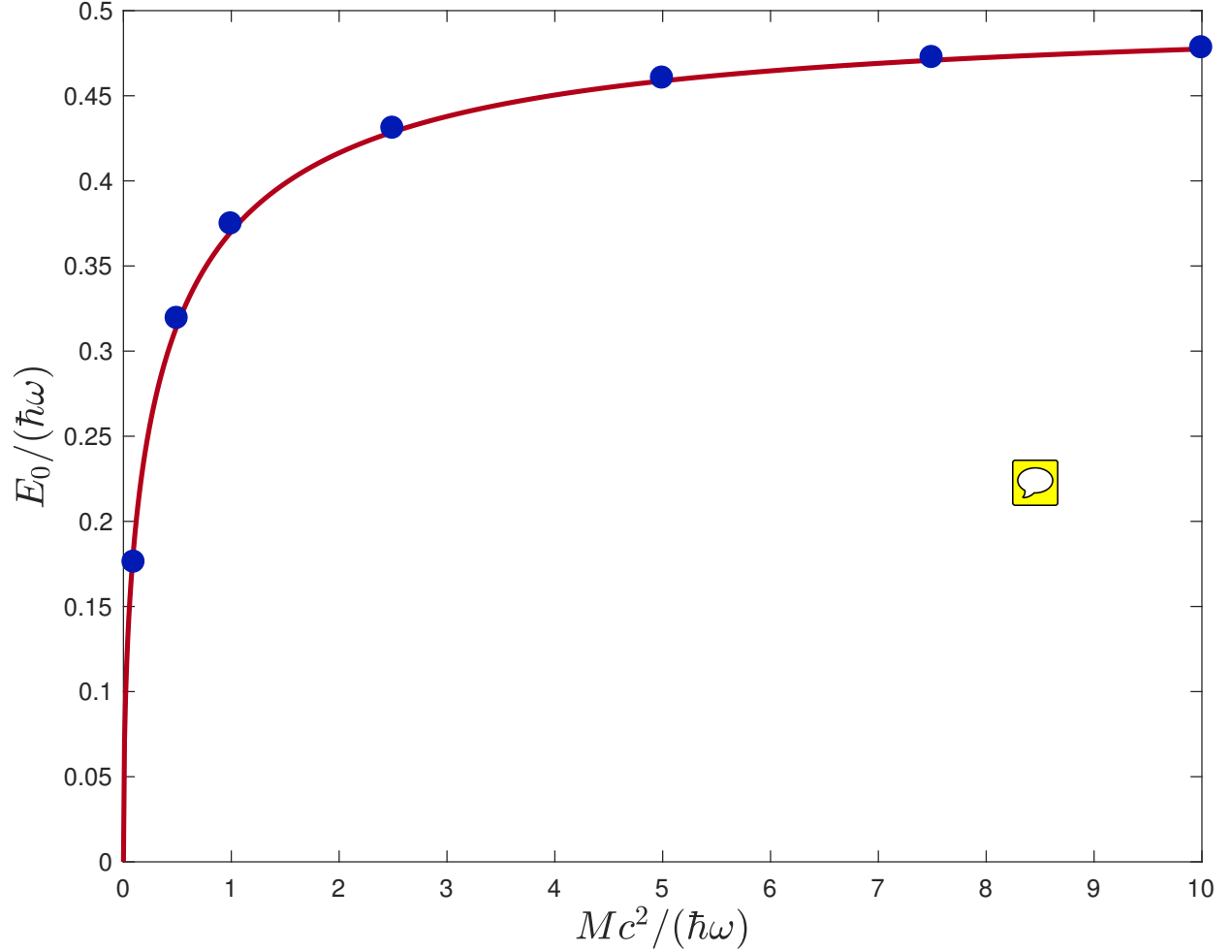


FIG. 1: Our hybrid Monte Carlo estimates (83–85, blue dots) of the ground-state energies $E_0/(\hbar\omega)$ of the Born-Infeld oscillator are plotted along with the exact values (Matlab, red curve) for $0.1 \leq Mc^2/(\hbar\omega) \leq 10$.

VII. THE HYBRID MODEL APPLIED TO A VERY AWKWARD ACTION

In this section, we test our hybrid method by using it to find the ground-state energy of the Born-Infeld oscillator considered as a theory with a very awkward action. That is, we pretend that we don't know the Born-Infeld hamiltonian (74) and use our hybrid method to evaluate the complex path integral (2) for its partition function. So instead of the partition

function (82), we have the partition function

$$\begin{aligned}
Z(\beta) &= \int \exp \left\{ \int^\beta \left[(i\dot{q} - \dot{s}) \frac{\partial L(q, \dot{s})}{\partial \dot{s}} + L(q, \dot{s}) \right] d^4x \right\} \left| \frac{\partial^2 L(q, \dot{s})}{\partial \dot{s}^2} \right| Dq D\dot{s} \\
&= \int \exp \left\{ \int^\beta \left[\frac{mi\dot{q}\dot{s} - m\omega^2 q^2 - M}{\sqrt{1 - m(\dot{s}^2 - \omega^2 q^2)/M}} + M \right] dt \right\} \\
&\quad \times \frac{m + m^2\omega^2 q^2/M}{[1 - m(\dot{s}^2 - \omega^2 q^2)/M]^{3/2}} Dq D\dot{s}.
\end{aligned} \tag{89}$$

We approximate this path integral on an $n \times n$ lattice of lattice spacing $a = \beta/n$ as the multiple integral

$$\begin{aligned}
Z(\beta) &= \prod_{j=1}^n \int \frac{d\dot{s}_j dq_j}{2\pi} \exp \left\{ \sum_{\ell=1}^n \left[\frac{i m(q_{\ell+1} - q_\ell)\dot{s}_\ell - am\omega^2 q_\ell^2 - aM}{\sqrt{1 - m(\dot{s}_\ell^2 - \omega^2 q_\ell^2)/M}} + aM \right] \right. \\
&\quad \times \left. \frac{m + m^2\omega^2 q_j^2/M}{[1 - m(\dot{s}_j^2 - \omega^2 q_j^2)/M]^{3/2}} \right\}.
\end{aligned} \tag{90}$$

Apart from the phase factor, the integrand is even in \dot{s} .

Sending $q_j \rightarrow \sqrt{M/m} q_j/\omega$, $\dot{s}_j \rightarrow \sqrt{M/m} \dot{s}_j$, and $a \rightarrow a/M$, we can write our lattice partition function as

$$\begin{aligned}
Z(\beta) &= \prod_{j=1}^n \int \frac{M d\dot{s}_j dq_j}{\omega 4\pi} \exp \left\{ \sum_{\ell=1}^n \left[\frac{i m(q_{\ell+1} - q_\ell)\dot{s}_\ell - am\omega^2 q_\ell^2 - aM}{\sqrt{1 - m(\dot{s}_\ell^2 - \omega^2 q_\ell^2)/M}} + aM \right] \right. \\
&\quad \times \left. \frac{m + m^2\omega^2 q_j^2/M}{[1 - m(\dot{s}_j^2 - \omega^2 q_j^2)/M]^{3/2}} \right\}.
\end{aligned} \tag{91}$$

We numerically compute the integrals

$$\begin{aligned}
A(q_{j+1}, q_j) &= \int_{-R(q_j)}^{R(q_j)} d\dot{s} \cos \left[\frac{M(q_{j+1} - q_j)\dot{s}}{\omega \sqrt{1 + q_j^2 - \dot{s}^2}} \right] \\
&\quad \times \exp a \left[1 - \frac{1 + q_j^2}{\sqrt{1 + q_j^2 - \dot{s}^2}} \right] \frac{1 + q_j^2}{[1 + q_j^2 - \dot{s}^2]^{3/2}}.
\end{aligned} \tag{92}$$

and

$$\begin{aligned}
C(q_{j+1}, q_j) &= M \int_{-R(q_j)}^{R(q_j)} d\dot{s} \left[\frac{q_j^2 + 1}{\sqrt{1 + q_j^2 - \dot{s}^2}} - 1 \right] \cos \left[\frac{M(q_{j+1} - q_j)\dot{s}}{\omega \sqrt{1 + q_j^2 - \dot{s}^2}} \right] \\
&\quad \times \exp a \left[1 - \frac{1 + q_j^2}{\sqrt{1 + q_j^2 - \dot{s}^2}} \right] \frac{1 + q_j^2}{[1 + q_j^2 - \dot{s}^2]^{3/2}}
\end{aligned} \tag{93}$$

and make a look-up table. We then use the look-up table to estimate the mean value

$$\langle H \rangle_\beta = \left\langle \frac{1}{n} \sum_{k=1}^n \frac{C(q_{k+1}, q_k)}{A(q_{k+1}, q_k)} \right\rangle. \quad (94)$$

We plotted our results as the green dots in Fig. 2 and listed them in Table II.

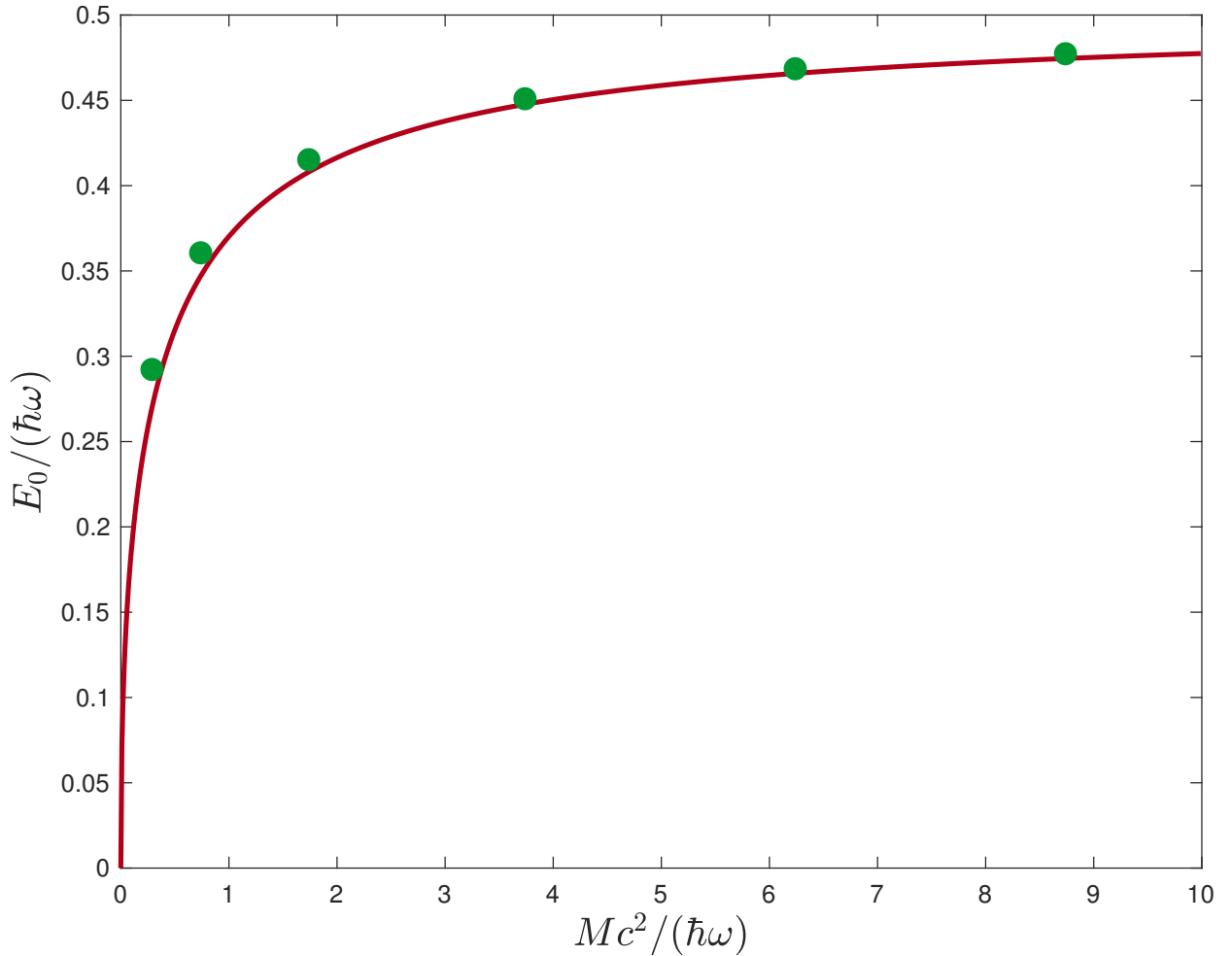


FIG. 2: Our hybrid Monte Carlo estimates (92–94, green dots) of the ground-state energies of the Born-Infeld oscillator are plotted along with the exact values (red curve) for $0.1 \leq Mc^2 / (\hbar\omega) \leq 10$.


TABLE II: Exact (Matlab) and hybrid Monte Carlo results (92–94) for the ground-state energies $E_0/(\hbar\omega)$ of the Born-Infeld oscillator (74) for $0.3 \leq Mc^2/(\hbar\omega) \leq 8.75$.

$M/(\hbar\omega)$	$E_0/(\hbar\omega)$ exact	$E_0/(\hbar\omega)$ Monte Carlo
0.3	0.2731	0.2915
0.75	0.3482	0.3599
1.75	0.4084	0.4145
3.75	0.4478	0.4502
6.25	0.4658	0.4678
8.75	0.4746	0.4766

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- [1] P. Ade and others (Planck Collaboration), *Astron. Astrophys.* **566**, A54 (2014) (2013).
 - [2] S. Boettcher and C. Bender, *J. Math. Phys.* **31**(11), 2579 (1990); K. Cahill, *Phys. Rev. D* **87**, 065024 (2013); **88**, 125014 (2013).
 - [3] A. Behtash, G. V. Dunne, T. Schaefer, T. Sulejmanpasic, and M. Unsal, (2015), arXiv:1510.03435 [hep-th]; L. Scorzato, *Proceedings, 33rd International Symposium on Lattice Field Theory (Lattice 2015): Kobe, Japan, July 14-18, 2015*, PoS **LATTICE2015**, 016 (2016), arXiv:1512.08039 [hep-lat]; C. Gattringer and K. Langfeld, *Int. J. Mod. Phys.* **A31**, 1643007 (2016), arXiv:1603.09517 [hep-lat].
 - [4] M. Born and L. Infeld, *Proc. Roy. Soc. Lond.* **A144**, 425 (1934); **A147**, 522 (1934); **A150**, 141 (1935).

- [5] M. Ostrogradsky, Mem. Acad. St. Petersburg VI **4**, 385 (1850); C. M. Bender and P. D. Mannheim, Phys. Rev. Letters **100**, 110402 (2008); J. Phys. A **41**, 304018 (2008).
- [6] P. A. M. Dirac, Can. J. Math. **2**, 129 (1950); Proc. Roy. Soc. London, ser. A **246**, 326 (1958); *Lectures on Quantum Mechanics* (Yeshiva University and Dover Publications, 1964).
- [7] K. Cahill, *Physical Mathematics* (Cambridge University Press, 2013) Chap. 19.
- [8] K. Cahill  *Physical Mathematics* (Cambridge University Press, 2013) Chap. 14.