Exact Born Approximation for the Spin-Boson Model

Daniel Loss\textsuperscript{1} and David P. DiVincenzo\textsuperscript{2}

\textsuperscript{1}Department of Physics and Astronomy, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland and

\textsuperscript{2}IBM Research Division, T. J. Watson Research Center, P.O. Box 218, Yorktown Heights, NY 10598, USA

(Dated: November 2, 2018)

Abstract

Within the lowest-order Born approximation, we present an exact calculation of the time dynamics of the spin-boson model in the Ohmic regime. We observe non-Markovian effects at zero temperature that scale with the system-bath coupling strength and cause qualitative changes in the evolution of coherence at intermediate times of order of the oscillation period. These changes could significantly affect the performance of these systems as qubits. In the biased case, we find a prompt loss of coherence at these intermediate times, whose decay rate is set by $\sqrt{\alpha}$, where $\alpha$ is the coupling strength to the environment. These calculations indicate precision experimental tests that could confirm or refute the validity of the spin-boson model in a variety of systems.
Novel solid state devices that can control spin degrees of freedom of individual electrons\cite{1,2}, or discrete quantum states in superconducting circuits\cite{3,4,5,6}, show promise in realizing the ideal of the completely controllable two-state quantum system, weakly coupled to its environment, that is the essential starting point for qubit operation in quantum computation. From a fundamental point of view, these experimental successes also bring us close to embodying the ideal test of quantum coherence as envisioned by Leggett many years ago\cite{7}, in which a simple quantum system is placed in a known initial state, is allowed to evolve for a definite time $t$ under the action of its own Hamiltonian and under the influence of decoherence from the environment, and is then measured.

Recent experiments, starting with\cite{4}, show that this ideal test can be implemented in practice. The decay of quantum oscillations due to environmental decoherence is now\cite{3,4,5,6} sufficiently weak that some tens of coherent oscillations can be observed. If quantum computation is to become a reality, it is believed\cite{8} that these systems will eventually need to achieve even lower levels of decoherence, such that thousands or tens of thousands of coherent oscillations could be observed. This prospect of producing experiments with ultra-long coherence times in quantum two state systems offers a new challenge for theoretical modelling of decoherence. Despite the many years of work\cite{9,10} following on Leggett’s initial proposals, there has never been a full, systematic analysis of the most popular description of these systems, the spin-boson model, in the limit of very weak coupling to the environment.

In this Letter we provide an exact analysis of the weak coupling limit of the spin boson model for the Ohmic heat bath, and in the low temperature limit. In this limit the Born approximation (to the self energy) should become essentially exact, and we make no other approximations in our solutions — in particular, no Markov approximation is made. As other workers have recently emphasized\cite{11,12}, understanding the details of the short-time dynamics of this model is especially crucial for the operation of these systems as qubits.

We find important, new, non-Markovian effects in this regime. At lowest order in the Born expansion of the self energy superoperator, the time dynamics of the model rigorously separates into a sum of strictly exponential pieces (the usual “$T_1$” and “$T_2$” decays of the Bloch-Redfield model) plus two distinct non-exponential pieces that arise, technically speaking, from two different kinds of branch cuts in the Laplace transform of the solution of the generalized master equation that we obtain.

These two contributions both have power-law forms at long times, $t > T_1, T_2$, and thus
formally dominate the exponentially-decaying parts. But more interesting is that they both give new structure to the time evolution at intermediate times \( t, 1/\omega_c < t < T_1, T_2; \) this structure typically occurs for \( t \) on the order of the oscillation period. (Here, \( \omega_c \) is a high frequency cut-off of the bath modes, defining the very short time regime, \( t < 1/\omega_c \), which is of no interest here.) We can explain our results in the language of the double-well potential, where the two quantum states are “left” and “right” \((L/R)\), the \( t = 0 \) state is pure \( L \), and the system oscillates in time via tunneling from \( L \) to \( R \). The first branch-cut contribution is most important in the unbiased case \((L \text{ and } R \text{ energies degenerate})\) and it causes the system, starting immediately in the first quantum oscillation, to spend more time in the \( R \) well, that is, the opposite well from the one the system is in initially. The second branch-cut contribution, present when the system is biased, adds to the amplitude of the coherent oscillation, but dies out after an intermediate time which scales like the inverse square root of the interaction strength \( \alpha \) with the bath. This prompt loss of coherence, whose amplitude is proportional to \( \alpha \), changes qualitatively the picture of the initial decay of coherence that is so important for discussions of fault-tolerant quantum computation \[13\].

We are interested in studying the time dependence of the system density matrix \( \rho_s(t) = \text{Tr}_B \rho(t) \) with a time-independent system Hamiltonian, and in the presence of a fixed coupling to an environment. An exact equation for \( \rho_s \) – the generalized master equation (GME) – is

\[
\dot{\rho}_S(t) = -iL_S\rho_S(t) - i\int_0^t dt'\Sigma_S(t-t')\rho_S(t'),
\]

\( \Sigma_S(t) = -i\text{Tr}_B L_{SB} e^{-iQLt} L_{SB} \rho_B. \)

Here the kernel \( \Sigma_S(t) \) is the self energy superoperator, the system-bath Hamiltonian is written \( H = H_S + H_{SB} + H_B \), the Liouvillian superoperator is defined by \( L_x \rho = [H_x, \rho] \), \( \rho_B = e^{-\beta H_B} / Z, \beta = 1/k_B T, T \) is the temperature, and \( Q \) is the projection superoperator \( Q = 1 - \rho_B \text{Tr}_B \). Eq. \( \text{(1)} \) is written for the case \( \text{Tr}_B H_{SB} \rho_B = 0 \), and the total initial state is taken to be of the form \( \rho(0) = \rho_S(0) \otimes \rho_B \). Since we are interested in the case of weak coupling to the bath, we will consider a systematic expansion in powers of this coupling \( L_{SB} \) in the self-energy operator \( \Sigma_S(t) \). Retention of only the lowest order term in this expansion, giving the Born approximation, is obtained \[15\] by the replacement \( e^{-iQlt} \rightarrow e^{-iQ(L_S+L_B)t} \) in Eq. \( \text{(2)} \).

We now proceed to solve the GME with no further approximations. This distinguishes
our work from previous efforts, in which various other approximations (secular, rotating wave, Markov, “non-interacting blips”, short time) are made (see, e.g., [7, 8, 9, 10, 11, 12]). We will find that, in particular, avoidance of the Markov approximation endows the solution with qualitatively new features.

We obtain our solution for the special case of a two-dimensional system Hilbert space, and a system-bath coupling of a simple bilinear form, \( H_{SB} = S \otimes X \) (\( S \) \( X \)) is an operator in the system (bath) space. In this case the GME in Born approximation can be rewritten in an ordinary operator form:

\[
\langle \dot{\sigma}_\mu(t) \rangle = -i \text{Tr}_S \sigma_\mu[H_S, \rho_S(t)] - \int_0^t dt' I_\mu(t, t'),
\]

\[
I_\mu(t, t') = I_{\mu 0}(t') + \sum_{\nu=1}^3 I_{\nu \mu}(t') \langle \sigma_\nu(t - t') \rangle,
\]

\[
I_{\mu \nu}(t') = \text{Re} \{ C(-t') \text{Tr}_S \sigma_\nu(-t') [\sigma_\mu, S] S(-t') \}.
\]

Here \( \sigma_{x,y,z} \) are the Pauli operators, \( \sigma_0 = I \), \( \langle x \rangle \equiv \text{Tr}_S x \rho_S \), the bath correlation function is \( C(t) \equiv \text{Tr}_B[XX(t)\rho_B] = C'(t) + i C''(t) \), the time dependent operators are in the interaction picture, i.e., \( o(t) = e^{i(H_S + H_B)t} o e^{-i(H_S + H_B)t} \), and \( C' \) and \( C'' \) denote the real and imaginary parts of the bath correlator.

Without loss of generality, we can take the system operators to be of the form

\[
H_S = \frac{\Delta}{2} \sigma_x + \frac{\epsilon}{2} \sigma_z
\]

and \( S = \sigma_z \). Then the GME can be written in an explicit form \( \langle \dot{\sigma}(t) \rangle = R \ast \langle \sigma \rangle + k \). Here \( \sigma \) denotes the vector \( (\sigma_x, \sigma_y, \sigma_z)^T \), convolution is denoted \( A \ast B \equiv \int_0^t dt' A(t')B(t - t') \), and

\[
R(t) = \begin{pmatrix}
-\frac{E^2}{\Delta^2} \Gamma_1(t) & -\epsilon \delta(t) + \frac{E}{\Delta} K_1^+(t) & 0 \\
\epsilon \delta(t) - \frac{E}{\Delta} K_1^+(t) & -\Gamma_1(t) & -\Delta \delta(t) \\
0 & \Delta \delta(t) & 0
\end{pmatrix},
\]

\[
k(t) = \left(-\frac{E}{\Delta} k_1^-(t), -k_1^-(t), 0\right)^T,
\]

with \( E = \sqrt{\epsilon^2 + \Delta^2} \), and kernels given by \( \Gamma_1(t) = \frac{4\Delta^2}{E^2} \cos(\epsilon t) C'(t) \), \( \Gamma_y(t) = \frac{4\Delta^2}{E^2} (1 + \frac{\epsilon^2}{\Delta^2} \cos(\epsilon t)) C''(t) \), \( K_1^+(t) = \frac{4\Delta^2}{E^2} \sin(\epsilon t) C'(t) \), \( k_1^-(t) = \frac{4\Delta^2}{E^2} \int_0^t dt' \sin(\epsilon t') C''(t') \), and \( k_y^-(t) = \frac{4\Delta^2}{E^2} \int_0^t dt' \sin(\epsilon t') C''(t') \).

These equations can be solved in the Laplace domain. Defining the Laplace transform as \( f(s) = \int_0^\infty e^{-st} f(t)dt \), the solutions are, for the “standard” initial conditions \( \langle \sigma(t = 0) \rangle = \)
For most of the sequel we will consider the Ohmic case, for which \( J_k \) kernels \( \Gamma \) solution in a Markov approximation. This approximation is obtained by replacing all the ultraviolet cutoff). In this case Eq. (12) becomes

\[
\langle \sigma_x(s) \rangle = \frac{1}{s + \frac{E^2}{\Delta} \Gamma_1(s)} \left( (\epsilon - \frac{E}{\Delta} K_y^+(s)) \frac{N(s)}{D(s)} - \frac{E}{\Delta} k^-(s) \right),
\]

\[
\langle \sigma_y(s) \rangle = -\frac{N(s)}{D(s)}, \quad \langle \sigma_z(s) \rangle = -\frac{\Delta N(s)}{s D(s)} + \frac{z_0}{s},
\]

\[
N(s) = \frac{E}{\Delta} \left( \epsilon - \frac{E}{\Delta} K_y^+(s) \right) k^-(s) + \left( \frac{\Delta}{s} z_0 + k^y_0 \right) \left( s + \frac{E^2}{\Delta^2} \Gamma_1(s) \right),
\]

\[
D(s) = \left( s + \Gamma_y(s) + \frac{\Delta_2}{s} \right) \left( s + \frac{E^2}{\Delta^2} \Gamma_1(s) \right) + \left( \epsilon - \frac{E}{\Delta} K_y^+(s) \right)^2.
\]

We can give more explicit solutions if we specialize to the spin-boson model, for which \( X = \sum_n c_n(b_n^+ + b_n) \) and \( H_B = \sum_n \omega_n b_n^+ b_n \). If the spectral function \( J(\omega) \) is defined as \( J(\omega) = \sum_n e_n^2 \delta(\omega - \omega_n) \), then

\[
C(t) = \int_0^\infty d\omega J(\omega) \left( \coth(\beta\omega/2) \cos(\omega t) + i \sin(\omega t) \right).
\]

For most of the sequel we will consider the Ohmic case, for which \( J(\omega) = \frac{\alpha}{\beta} \omega e^{-\omega/\omega_c} (\omega_c \) is an ultraviolet cutoff). In this case Eq. (12) becomes

\[
C(t) = -\frac{\alpha}{\beta^2} \text{Re} \psi' \left( 1 - \frac{i \omega_c t}{\beta \omega_c} \right) + \frac{\omega_c^2}{2} \frac{1 - \omega_c^2 t^2}{(1 + \omega_c^2 t^2)^2} + i \frac{\alpha \omega_c^2}{2} \frac{\omega_c t}{(1 + \omega_c^2 t^2)^2},
\]

where \( \psi' \) is the derivative of the digamma function.  

For discussing the exact solution it is instructive to understand the structure of the solution in a Markov approximation. This approximation is obtained by replacing all the kernels \( \Gamma_1, \Gamma_y, K_y^+, k^-, k_y^- \) by their values at \( s = 0 \). In this case the solutions Eqs. (9) are rational functions of \( s \). Then, if the poles of these rational functions are located at positions \( s_k \) in the complex \( s \) plane, with residues \( r_k/2\pi i \), then the inverse Laplace transform can be written \( \langle \sigma_\mu(t) \rangle = \sum_k r_k^\mu \exp(s_k t) \). We indicate here that while the residues do depend on the label \( \mu = x, y, z \), the pole positions do not, as is suggested by the form of Eqs. (9).

As is well known, there are four poles: \( s_1 = 0, s_2 = -\Gamma_1, \) and \( s_{3,4} = -\Gamma_2 \pm i\tilde{E} \). The first pole describes the long-time asymptote of the solution (stationary state), the second the purely exponential, “\( T_1 \)”-type decay (relaxation), and the last two (complex conjugate paired) describe an exponentially decaying sinusoidal part, the “\( T_2 \)”-type decay of coherent oscillations. The residues of these poles are, to lowest order in \( \alpha, r_1^x = x_\infty = - (\Delta/E) \tanh(\beta E/2), r_1^y = y_\infty = 0, r_2^z = z_\infty = - (\epsilon/E) \tanh(\beta E/2), r_2^{y} = \epsilon \Delta/E^2 - x_\infty, r_2^{y} = 0, r_2^{z} = \epsilon^2/E^2 - z_\infty, r_3^{x,4} = -\epsilon \Delta/2E^2, r_3^{y,4} = -\Delta/2E, \) and \( r_3^{x,4} = \Delta^2/2E^2 \). The pole
positions are, again to lowest order in $\alpha$, given by 
$$
\Gamma_0^1 = T_1^{-1} = \frac{\alpha \Delta^2}{E} \coth(\beta E/2), \quad \Gamma_0^2 = T_2^{-1} = \Gamma_1^0/2 + \frac{2\alpha^2}{E^2} k_B T, \quad \text{and} \quad \tilde{E} = E + \delta E, \quad \delta E = \delta E_{\text{Lamb}} + \delta E_{\text{Stark}} \quad [18],$$
where we have dropped terms of order $E/\omega_c$ and higher, $C$ is the Euler constant, and $\psi$ is the digamma function \[17\]. These expressions are straightforwardly derivable, and agree with the literature \[9\], except for the energy shift due to vacuum fluctuations, $\delta E_{\text{Lamb}}$ (which contains in general $\ln(E/\omega_c)$ and not $\ln(\Delta/\omega_c)$). We note that this Markovian theory satisfies the expected fundamental relation 
$$
\Gamma_0^2 = \frac{\Gamma_0^1}{2} + \frac{2\alpha^2}{E^2} \int_{-\infty}^{\infty} dt \langle X(t) X \rangle_B \quad \text{(Korringa relation)} \quad [20];$$
also, to lowest order in $\alpha$, the asymptotic values of $\langle \sigma_{\mu}(t \to \infty) \rangle$ go to the Boltzmann equilibrium distribution of the system, e.g., $z_{\infty} = - (\epsilon/E) \tanh(\beta E/2)$, unlike, for example, the popular “non-interacting blip” approximation \[9\].

We now return to the exact solution, examining it in detail at vanishing temperature $T = 0$. In this case the Laplace transform of $C$ in Eq. \[13\] is

$$
C_{T=0}(s) = \alpha s/2 \left( - \cos(\tilde{s}) \text{Ci}(\tilde{s}) - \sin(\tilde{s}) \text{si}(\tilde{s}) \right) \\
- i\alpha/2 \left( -\omega_c + s \sin(\tilde{s}) \text{Ci}(\tilde{s}) - s \cos(\tilde{s}) \text{si}(\tilde{s}) \right),
$$
where $\tilde{s} = s/\omega_c \quad [19]$. There is an important feature of this correlation function that makes the Markov solution qualitatively incomplete: while the sine integral $\text{si}$ is analytic, the cosine integral $\text{Ci}(s)$ behaves like $\ln(s)$ for $s \to 0 \quad [17]$. This means that $C(s)$ is nonanalytic at $s = 0$ — it has a branch point there. Thus, the exact solutions $\langle \sigma_{\mu}(s) \rangle$ have extra analytic structure not present in the Markov approximation, and the real-time dynamics $\langle \sigma_{\mu}(t) \rangle$ has qualitatively different features in addition to the pole contributions we have just discussed.

The $s = 0$ branch point in $C(s)$ leads the kernels $\Gamma_1(s)$, $K_+^y(s)$, and $k_-(s)$ to have branch points at $s = \pm iE$; the kernels $\Gamma_2(s)$ and $k_0^-(s)$ have three branch points, at $s = 0$ and $s = \pm iE$. Thus, the solutions to the GME $\langle \sigma_{x,y,z}(s) \rangle$ also have three branch points in the complex plane. We find by numerical study that the exact solutions still have four poles as before, which, for small $\alpha$, have nearly (but not exactly) the same pole positions and residues as in the Markov approximation.

Thus, the structure of the solutions in the complex $s$ plane is as shown in Fig. \[1a\]. The locations of the branch cuts are chosen for computational convenience, as discussed shortly. Given this branch-cut structure, the inverse Laplace transform (the Bromwich integral) is evaluated by closing the contour as shown. Thus, the exact inverse Laplace transform can
be expressed as \((t > 0)\)

\[
\langle \sigma_\mu(t) \rangle = \frac{1}{2\pi i} \oint_C dse^{st} \langle \sigma_\mu(s) \rangle = \frac{1}{2\pi i} \oint_{C_0} dse^{st} \langle \sigma_\mu(s) \rangle - \frac{1}{2\pi i} \sum_{k=1}^{3} q_k \int_{p_k}^{\infty} dx e^{q_k x t} (\langle \sigma_\mu(q_k x + \eta_k) \rangle - \langle \sigma_\mu(q_k x - \eta_k) \rangle).
\]

Here \(q_k = e^{i\theta_k}\) and \(\eta_k = \eta e^{i(\theta_k - \pi/2)}\), with \(\eta\) an infinitesimal positive real number. That is, \(\eta_k\) is an infinitesimal displacement perpendicular to the direction of branch cut \(k\). For the cut choices we have made, \(\theta_1 = 5\pi/4, \theta_2 = \pi/2, \theta_3 = 3\pi/2, p_1 = 0,\) and \(p_2 = p_3 = E\). The closed-contour integral in the expression can be written as a sum over the four poles, and so gives complex exponential contributions to the solution as in the Markovian case. The extra terms, the sum over the three branch cuts, are new and give qualitatively different features.

The contributions of the second and third branch cuts are complex conjugates of each other, so we will discuss them together as the “branch cut 2” (“bc2” for short) contribution. The first cut will be discussed as the “bc1” contribution.

The contribution of these cuts to the solution is independent of the detailed positioning of the branch cuts, so long as they are not moved across a pole; the choice of the direction of bc1 is a computational convenience — the apparently most natural choice of this cut direction, along the negative real axis, passes it essentially on top of the \(\Gamma_1\) pole, making the evaluation of the branch-cut integral numerically inconvenient. As a check, we find that the results we discuss now are indeed independent of the cut direction.

We have done a detailed study of these branch-cut contributions for \(\langle \sigma_z(t) \rangle \equiv z(t)\). For the unbiased spin-boson case, \(\epsilon = 0\), an essentially analytic calculation can be done for all contributions. In this case there is no bc2 contribution, \(z_{bc2} = 0\). The bc1 contribution can be obtained analytically to leading order in \(\alpha\):

\[
z_{bc1}(t) = -\alpha \left\{ 1 - \Delta t [\text{Ci}(\Delta t) \sin(\Delta t) - \text{si}(\Delta t) \cos(\Delta t)] \right\}.
\]

This function, plotted along with the pole contribution in Fig. 1b for the choice of parameters shown, has the following features: \(z_{bc1}(t)\) is negative for all \(t\), it is monotonically increasing, and its long-time behavior is \(z_{bc1}(t) \sim -2\alpha/(\Delta t)^2\). Also, \(z_{bc1}(t = 0) = -\alpha\).

Let us survey, then, the peculiar features that this branch cut contribution introduces into the time response \(z(t)\). Visualizing the \(\epsilon = 0\) spin-boson model as a symmetric double well system coupled to its environment, the bc1 piece being negative means that, if the
system is initially in the left well, it will, in the course of coherently tunnelling back and forth, spend more time in the right well! This effect becomes strongest at long time, much longer than $T_2$, for in this regime the pole contributions are exponentially small, while the bc1 contribution decays like a power law. Experimentally it may be hard to see the effect in this regime (on account of finite-temperature effects, for example), so it is important to note that this memory effect appears already at early times, indicating that already in the first couple of coherent oscillations, there will be an excess amplitude in the right-well excursions as compared with the left-well excursions, by an amount proportional to $\alpha$. We believe, on the basis of a variety of evidence\[21\], that the Born approximation should be reliable up to $\alpha$’s of order $1 – 2\%$; thus, experiments that look at coherent oscillations accurately at the percent level (which, it seems, will ultimately be necessary for performing quantum computation) could readily see this bc1 effect.

We note several other interesting features of our solution for $\epsilon = 0$. Taking into account the non-Markovian effects, we can do a more precise calculation of the pole positions and residues (only poles 3 and 4 contribute). We find, for $T = 0, \Gamma_2 \equiv -\text{Re}(s_3) = \Gamma_2^0 r$, where, as before $\Gamma_2^0 = \alpha \pi \Delta/2$, and the renormalization factor $r$ is given by $r = (1 - \alpha)/(\kappa^2 + \alpha^2 \pi^2) < 1$, with $\kappa = 1 - 2\alpha(1/2 + C + \ln(\Delta/\omega_c))$. Further, $\text{Im}(s_3) = E + \delta E^{\text{Lamb}} \tilde{r}$, with $\tilde{r} = (\kappa - \alpha \pi^2/2(C + \ln(\Delta/\omega_c)))/(\kappa^2 + (\alpha \pi)^2)$. These expressions are obtained as systematic expansions in the small parameters $\Gamma_2/E$ and $\delta E/E$, and they match a direct numerical evaluation of the pole positions very well up to $\alpha$’s of a few percent. For the corresponding pole residues we find the simple result in leading order $r_3 + r_4 = 1 + \alpha + O(\alpha^2)$. This would be impossible in a Markovian theory, in which $z(t = 0) = r_3 + r_4$, so that $r_3 + r_4$ would be exactly 1 to all orders in $\alpha$. In fact this excess pole residue is exactly what is needed to cancel out the initial value of the bc1 contribution to $z(t)$. We note that our results for the residues differ from the weak-coupling expressions in the literature\[9\] (we are not aware of prior reports on $r, \tilde{r}$).

For the biased model ($\epsilon \neq 0$) the bc2 contributions become nonzero; we find that they give other peculiar non-exponential corrections to the solution $z(t)$, very different from the bc1 contribution. We can do a nearly analytic evaluation of the bc2 contribution to Eq. (15): Using Eq. (9) and expanding to lowest order in $\alpha$, we find for the integrand of the
sum of the $k = 2$ and $3$ terms of (15),

$$z_{bc2}(s = i\omega) \approx \frac{2\Delta^2}{\omega} \frac{b^-(\omega)}{(E^2 - \omega^2 + b^+(\omega))^2 + b^-(\omega)^2}.$$  \hspace{1cm}  (17)

Here $b(i\omega \pm \eta) \equiv b^+(\omega) \pm \frac{ib^-}{b}(\omega)$, $b(s) \equiv \alpha(d(s) + n(s)(s^2 + E^2)/\Delta)$, where $d(s)$ and $n(s)$ are given by $N(s) = \Delta + \alpha n(s)$ (see Eq. (10)) and $D(s) = s^2 + E^2 + \alpha d(s)$ (see Eq. (11)).

Since $b^-(\omega) = 0$ for $|\omega| \leq E$, it is reasonable to expect that $b^-$ will grow linearly as one passes onto the branch cut; and, in fact, we find from numerical study that a good ansatz is $b^- = (E - \omega)\tilde{b}^-(\omega)$, with $\tilde{b}^-$ being a weakly varying, real function of $\omega / E$. With this, for $\omega$ of order $E$, Eq. (17) simplifies to

$$z_{bc2}(s = i\omega) \approx -\frac{\Delta^2\tilde{b}^-(E)}{2E^3} \frac{1}{\omega - E}.$$  \hspace{1cm}  (18)

We find that (18) should be valid for $\omega > E + b^+(E)/2E$. Using (18) we can do the branch cut integral, which gives (for $t \leq 1/(\alpha Ex_0)$ — see Appendix for an alternative approach),

$$z_{bc2}(t) \approx \alpha x_1 \log(x_0 \alpha Et) \cos(Et + \phi).$$  \hspace{1cm}  (19)

Here the dimensionless constants $x_0 = |b^+(E)| / 2\alpha E^2 = |\delta E| / \alpha E$ and $x_1 = \Delta^2\tilde{b}^-(E) / 2\alpha E^3$. Since $b^+ \propto \alpha$, these constants are independent of $\alpha$. The last expression for $x_0$ comes from an evaluation of $b^+(E)$: it is directly related to the energy renormalization in the Markov approximation, $b^+(E) = 2E\delta E^{\text{Lamb}}$.

In Fig. 2 we show a direct numerical evaluation of $z_{bc2}(t)$. One can see the decay of the oscillatory part, which is logarithmic according to Eq. (19). Even though the decay is very non-exponential, it is reasonable to attempt to characterize this decay by a time scale. Eq. (19) obviously does not work at $t = 0$, since it is logarithmically divergent. This is not surprising, since our calculation has neglected cutoff effects (dependence on $\omega_c$), so Eq. (19) is not expected to be correct for $t < 1/\omega_c$. However, if we consider “early” time to be the first half-period of the coherent oscillation, $t_0 = \pi / E$, then Eq. (19) should be valid and we can use it to characterize the decay by determining the time $t_h$ at which $z_{bc2}(t)$ decreases to half its early-time value, i.e., $z_{bc2}(t_h) = \frac{1}{2}z_{bc2}(t_0)$. We obtain

$$t_h = \frac{1}{E} \sqrt{\frac{\pi E}{|\delta E|}} \propto \frac{1}{E} \sqrt{\alpha}.$$  \hspace{1cm}  (20)

Surprisingly, $t_h \propto 1/\sqrt{\alpha}$ depends non-analytically on $\alpha$. This explains the effect that is evident in Fig. 2: for small $\alpha$, $t_h \ll T_2$, that is, on the scale of $T_2$, there is a very rapid
loss of coherence as contributed by bc2. This phenomenon may be called a prompt loss of coherence, as it would appear experimentally as a fast initial loss of coherence (from 100% to \((1 - c\alpha)100\%\), \(c\) being some constant near unity), followed by a much slower, exponential decay of coherence on the regular \(T_2\) time scale.

We give a few final remarks about the bc2 calculation. The absolute size of the bc2 contribution reaches a maximum near the value of \(\epsilon/\Delta\) used in Fig. 2; the relative size of this contribution continues to increase as \(|\epsilon|/\Delta\) increases, so that it eventually becomes much larger than the pole contribution (but all contributions to \(z(t)\) go to zero as \(|\epsilon|/\Delta \rightarrow \infty\)). When \(|\epsilon| \approx \Delta\), we find that, because of the prompt loss of coherence, there is a deficit in the total pole contribution, that is, \(\sum_k r_k = 1 - O(\alpha) < 1\). Even in the absence of an explicit branch cut computation, this deficit signals the prompt loss of coherence, in that it indicates that the exponentially decaying contributions to \(z(t)\) do no account for all the coherence near \(t = 0\). Note that this is opposite to the unbiased case, where, as a result of the bc1 part, there is an excess pole contribution.

Naturally, many more regimes could be studied using the present approach. Recently, there has been interest in varying both the system and bath initial conditions, as well as in varying the model of the bath density of states. For all these circumstances, the systematic Born expansion procedure we report here can be done. It is clear on general grounds that the appearance of branch cut contributions will not be restricted to the Ohmic model we have studied in detail here; it is easy to show that for any spectral density of the form \(J(\omega) \propto \omega^n\) at low frequencies \((n = 0, 1, 2, ...)\), \(C(t)\) will have a power-law dependence at long time, and thus \(C(s)\) will have a branch point at \(s = 0\). So, interesting non-exponential contributions to the dynamics are expected in all these cases.

Our hope is that, using the present and further exact calculations of the weak-coupling behavior of the spin-boson model, a tool will be made available to permit precision experiments to test the validity of the model (which, at present, is only phenomenologically justified) in various physical situations of present interest in quantum information. A fundamentally correct, experimentally verified theory of the system and its environment should ultimately be of great value in finding a satisfactory qubit for the construction of a quantum information processor.

DPDV is supported in part by the National Security Agency and the Advanced Research and Development Activity through Army Research Office contract number DAAD19-01-C-
0056. He thanks the Institute for Quantum Information at Cal Tech (supported by the National Science Foundation under Grant No. EIA-0086038) for its hospitality during the initial stages of this work. DL thanks the Swiss NSF, NCCR Nanoscience, DARPA and the ARO.

[1] R. Hanson et al., “Zeeman energy and spin relaxation in a one-electron quantum dot,” cond-mat/0303139

[2] D. Loss and D. P. DiVincenzo, “Quantum Computing with Quantum Dots,” Phys. Rev. A 57, 120 (1998), cond-mat/9701055

[3] Yu. Makhlin, G. Schönh, and A. Shnirman, “Quantum state engineering with Josephson-junction devices,” Rev. Mod. Phys. 73, 357-400 (2001), cond-mat/0011269

[4] Y. Nakamura, Yu. A. Pashkin, and J. S. Tsai, “Coherent control of macroscopic quantum states in a single-Cooper-pair box,” Nature 398, 786-788 (1999); Yu. A. Pashkin, T. Yamamoto, O. Astafiev, Y. Nakamura, D. V. Averin, and J. S. Tsai, “Quantum oscillations in two coupled charge qubits,” Nature 421, 823-826 (2003).

[5] I. Chiorescu, Y. Nakamura, C. J. P. M. Harmans, and J. E. Mooij, “Coherent Quantum Dynamics of a Superconducting Flux Qubit,” Science 299, 1869-1871 (2003).

[6] D. Vion et al., “Manipulating the quantum state of an electrical circuit,” Science 296, 886-889 (2002).

[7] A. J. Leggett et al., Rev. Mod. Phys. 59, 1 (1987).

[8] D. P. DiVincenzo and D. Loss, “Quantum Computers and Quantum Coherence,” J. of Magnetism and Magnetic Matls. 200, 202 (1999), cond-mat/9901137

[9] U. Weiss, Quantum Dissipative Systems (World Scientific, Singapore, Second Edition, 1999).

[10] M. Grifoni and P. Haenggi, “Driven Quantum Tunneling,” Phys. Rep. 304, 229-358 (1998).

[11] Daniel Braun, Fritz Haake, and Walter T. Strunz, Phys. Rev. Lett. 86, 2913 (2001) (quant-ph/0006117); Walter T. Strunz, Fritz Haake, and Daniel Braun, Phys. Rev. A 67, 022101 (2003) (quant-ph/0204129).

[12] V. Privman, “Onset of Decoherence in Open Quantum Systems,” cond-mat/0303157
   “Initial Decoherence of Open Quantum Systems,” J. Stat. Phys. 110, 957-970 (2003), quant-ph/0205037
APPENDIX A: SCALING FORM FOR BRANCH CUT INTEGRALS

By numerical study we find that the branch cut integrals conform to some simple scaling laws for small $\alpha$. If we write the bc1 and bc2 integrals as

$$z_{bc1}(t) = \int_0^\infty dx e^{-q_1 xt} z_{bc1}(s = q_1 x)$$

and

$$z_{bc2}(t) = \text{Re} \int_0^\infty dxe^{xt} z_{bc2}(s = ix),$$

then we find that for small $\alpha$ and for $s << \omega_c$, $z_{bc1}(s)$ can be written in a scaling form

$$z_{bc1}(x) = (\alpha/E) f_1(\epsilon/\Delta, x/E).$$

(A1)

But for bc2 a very different scaling law applies:

$$z_{bc2}(x) = (1/E) f_2(\epsilon/\Delta, (x - E)/\alpha E).$$

(A2)

Here $f_{1,2}$ are dimensionless, “universal” functions that govern the behavior of the branch cut contributions for small $\alpha$. For bc1, the behavior that the scaling law gives is very simple: Eq. (A1) implies that $z_{bc1}(t) = \alpha \tilde{f}_1(\epsilon/\Delta, Et)$, where $\tilde{f}_1$ is the Laplace transform of the scaling function $f_1$. We might have expected this behavior from Eq. (16), from which we can read...
off the scaling function for $\epsilon = 0$. In fact it appears from numerical studies that $f_1$ hardly changes as $\epsilon$ is varied, except for an overall scale factor; that is, $\bar{f}_1(\epsilon/\Delta, Et) \approx a(\epsilon/\Delta)b(Et)$.

We find that the scaling function $a(\tau) > 0$ is peaked at $\tau = 0$. So, the memory effect described above for $\epsilon = 0$ persists for finite $\epsilon$, but becomes smaller. For $|\epsilon| \approx \Delta$ the bc2 contribution, which we will describe now, becomes dominant over the bc1 one.

Returning to Eq. (A2), if we write the Fourier transform of the scaling function as $\bar{f}_2(\tau) = \int_0^\infty e^{ix\tau}f_2(x)dx$ and consider its polar form $\bar{f}_2(\tau) = r_2(\tau)e^{i\phi_2(\tau)}$, then we obtain

$$z_{bc2}(t) = \alpha r_2(\alpha Et)\cos(\phi)\cos(\phi_2(\alpha Et)).$$

(A3)

This shows that bc2 contributes an oscillatory part to the solution, whose “$T_2$” decay is determined by the features of the scaling function $r_2$. A few more observations about $f_2$ (obtained initially from numerical study) reveal some crucial properties of the $r_2$ function:

1) $f_2(0) = 0$; 2) $|f_2(x)|$ has a single maximum at $x = x_0$, where $x_0$ is some constant of order unity; 3) Most important for the present discussion, for $x > x_0$ $f_2(x)$ approaches $1/x$, that is, $f_2(x) \sim x_1/x$, where $x_1$ is another real constant of order unity. Fact 3) implies that, for $\tau \to 0$, $r_2(\tau) \approx x_1\log(x_0\tau)$. That is, we conclude that at sufficiently short time (actually for $t \leq 1/(\alpha Ex_0)$, so a relatively long time),

$$z_{bc2}(t) = \alpha x_1\log(x_0\alpha Et)\cos(\phi),$$

(A4)

as stated in the text.
FIG. 1: (a) Structure of the solutions $\langle \sigma_\mu(s) \rangle$ in the complex $s$ plane. The four poles $p_1, p_2, p_3$, and $p_4$, are indicated by crosses; the three branch points at $s = 0, \pm iE$ are indicated by solid circles, and the three branch cuts chosen, bc1, bc2, and bc3, are indicated by dashed lines. The inverse Laplace transform requires an integration along the contour $C$ parallel to the imaginary axis. This integral may be evaluated by closing with a contour in the left half plane ($C_0$, the Bromwich contour), which lies at infinity except for looping back around each of the branch cuts.

(b) $z_{\text{poles}}(t)$ and $z_{\text{bc1}}(t)$ for the unbiased case, $\epsilon = 0$, $\Delta = 1$, $\omega_c = 30$, $T = 0$, and $\alpha = 0.01$. $t$ is in units of $1/E$ (i.e., $E = 1$).
FIG. 2: $z_{\text{poles}}(t)$ and $z_{bc2}(t)$ for the biased case, illustrating the prompt loss of coherence produced by bc2. Here $E = 1$, $\epsilon/\Delta = -1.38$, $\omega_c = 30$, $T = 0$, and $\alpha = 0.01$. For these parameters, the time scale for the prompt loss of coherence (using Eq. (20)) is $t_h = 18.98$. $t_h$ is the time at which the envelope of $z_{bc2}$ falls to half its value at $t_0 = \pi/E$. This time scale is much shorter than the regular exponential decay of coherence in $z_{\text{poles}}$; for our parameters, $T_2 = 204.6$. 