ABSTRACT. We find the leading asymptotics of the exponentially small splitting of the two lowest eigenvalues of $-\frac{1}{2}\Delta + \lambda^2 V$ in the limit as $\lambda \to \infty$ where $V$ is a nonnegative potential with two zeros.

In this note, we consider eigenvalues of a Schrödinger operator $-\frac{1}{2}\Delta + \lambda^2 V$ in the limit $\lambda \to \infty$ (which is quasiclassical since up to a factor of $\hbar^2$, $-\hbar^2\Delta + V$ has this form with $\hbar = \lambda^{-1}$ going to zero). The method can deal with eigenvalues other than the lowest, with multiple minima (even manifolds of minima) or degenerate minima. In this note, for simplicity we discuss only the two lowest eigenvalues, $E_0(\lambda)$ and $E_1(\lambda)$, with corresponding normalized eigenvectors $\Omega_0(\lambda)$, $\Omega_1(\lambda)$. More general situations and detailed proofs will appear elsewhere [13]. We will suppose the following about $V$.

(i) $V$ is $C^\infty$, (ii) $V(x) > 0$ for all $x$ and $\lim_{|x| \to \infty} V(x) > 0$, (iii) $V$ vanishes at exactly two points $a$ and $b$ and at these points $\frac{\partial^2 V}{\partial x_i \partial x_j}$ is strictly positive definite.

Under these circumstances, one can prove (see e.g. [12]) that $\psi_0$ is concentrated as $\lambda \to \infty$ near the points $a$, $b$ and that $E_1(\lambda)/\lambda$ has a finite nonzero limit. We want also to suppose that for all $\epsilon$ small and for $y = a$ and for $y = b$

$$\lim_{\lambda \to \infty} \int_{|x-y| \leq \epsilon} |\psi_0(\lambda, x)|^2 dx > 0.$$  

One case where (1) holds is when there is a symmetry of order 2 (such as reflection) which leaves $V$ and $-\Delta$ invariant, so that the limit is $\frac{1}{2}$ for $y = a$ or $b$.

Under these circumstances, one expects that the splitting of $E_1$ and $E_0$ will be governed by tunneling and one goal here is to obtain multidimensional
tunneling results. A basic geometric object which will enter is the Agmon metric defined by

\[ \rho(x, y) = \inf_{\gamma} \left( \int_0^1 \sqrt{2V(\gamma(s))|\gamma'(s)|} \, ds \mid \gamma(0) = x, \gamma(1) = y \right) \]

that is the geodesic distance in the metric \(2V(x)dx^2\). It is an elementary fact (see e.g. [3]) that

\[ \rho(x, y) = \inf_{\gamma, T} \left( \frac{1}{2} \int_0^T \gamma'(s)^2 \, ds + \int_0^T V(\gamma(s)) \, ds \mid \gamma(0) = x, \gamma(T) = y \right). \]

One basic result is

**THEOREM 1.** Under the above hypotheses on \(V\) (including (1))

\[ \lim_{\lambda \to \infty} \left\{ -\frac{1}{\lambda} \ln |E_1(\lambda) - E_0(\lambda)| \right\} = \rho(a, b). \]

For the special case of one dimension (and for some slightly different multidimensional problems where the geodesic is a straight line), Harrell [7, 8] has proven (4); indeed, he has obtained even more than the leading asymptotics. Combes et al. [5] has announced further results on the one-dimensional case. Our result here is the first rigorous result on leading asymptotics in intrinsically multidimensional double wells.

The geodesic from \(a\) to \(b\) parameterized to minimize (3) (the path must go from \(a\) at \(t = -\infty\) to \(b\) at \(t = \infty\)) is called an instanton and that the instanton should control the splitting has been discussed in the theoretical physics literature for several years; see e.g. [4, 6].

The Agmon metric was introduced by Agmon [1] (see also [2 and 3]) to discuss decay of eigenfunctions as \(x \to \infty\) and it enters here also through decay of eigenfunctions. Indeed, Theorem 1 is proven using

**THEOREM 2.**

\[ \lim_{\lambda \to \infty} \left\{ -\frac{1}{\lambda} \ln \Omega_0(\lambda, x) \right\} = \min(\rho(x, a), \rho(x, b)) \]

where the limit is uniform on compact subsets of \(x\). Moreover, for some \(R\) and \(d > 0\),

\[ |\Omega_0(\lambda, x)| \leq Ce^{-d|x|} \]

if \(|x| > R\).

To prove Theorem 1, given Theorem 2, one uses

\[ E_1 - E_0 = \inf \left( \int (\nabla f)^2 \Omega_0^2 \, dx / \int f^2 \Omega_0^2 \, dx \right) \]

the inf being over all \(f\) with \(\int f \Omega_0^2 \, dx = 0\). To get the upper bound in (4), we pick an \(f\) obeying this condition and \(\int f^2 \Omega_0^2 = 1\) (\(f\) is bounded by (1)), so that \(\nabla f\) is concentrated in a neighborhood of the geodesic bisector (points with \(\rho(x, a) = \rho(x, b)\)) and then use Theorem 2 and the fact that \(\rho(x, a) \geq \frac{1}{2} \rho(a, b)\)
for any such $x$. We get the lower bound by looking at the contribution to (7) of a small tube about the geodesic from $a$ to $b$ using the fact that for any $x$ on the geodesic, $\min(\rho(x, a), \rho(x, b)) \leq \frac{1}{2} \rho(a, b)$.

One can prove Theorem 2 by using the differential equation methods of Agmon [2] (see [13]). We prefer an alternative proof, which was our original one, which depends on the method of large deviations, a procedure of estimating asymptotics of path integrals [14]. Let $e^{-tH(\lambda)}(x, y)$ denote the integral kernel of the semigroup generated by $H(\lambda) \equiv -\Delta + \lambda x^2$. Using the Feynman-Kac formula (see e.g. [11]) and thinking of Brownian motion as formally $\int d\infty b\delta(b(0))e^{-\int \frac{b''}{2}}$, we find after scaling that formally

$$\exp(-TH(\lambda)/\lambda)(x, y) = \int d\infty b\delta(b(0) - x)\delta(b(T) - y)\exp\left[-\frac{\lambda}{2} \int_0^T b^2(s)ds - \lambda \int_0^T V(b(s))ds\right].$$

This suggests the following result, which can be proven by the methods of Schilder [10] and Pincus [9].

**Theorem 3.**

$$\lim_{\lambda \to \infty} -\lambda^{-1} \ln|\exp(-TH(\lambda)/\lambda)(x, y)| = A(x, y; T)$$

where the limit is uniform on compact sets of $x, y, T$ and where

$$A(x, y; T) \equiv \inf\left(\frac{1}{2} \int_0^T \dot{\gamma}(s)^2ds + \int_0^T V(\gamma(s))ds \mid \gamma(0) = x, \gamma(T) = y\right).$$

The lower bound in (5) now follows by noting that

$$\Omega_0(\lambda, x) \geq \left[\min_{|y - a| \leq \epsilon} e^{-TH(\lambda)/\lambda}(x, y)\right] \int_{|y - a| \leq \epsilon} \Omega_0(\lambda, y)dy + \left[\min_{|y - b| \leq \epsilon} e^{-TH(\lambda)/\lambda}(x, y)\right] \int_{|y - b| \leq \epsilon} \Omega_0(\lambda, y)dy$$

and that $\lim_{T \to \infty} A(x, a; T) = \rho(x, a)$ (and similarly for $b$). The upper bound in (5) comes from

$$|\Omega_0(\lambda, x)|^2 \leq e^{TE_0(\lambda)/\lambda} e^{-TH(\lambda)/\lambda}(x, x)$$

and the interesting fact that

**Lemma.**

$$\lim_{T \to \infty} A(x, x; T) \equiv \min(2\rho(x, a), 2\rho(x, b)).$$

**Sketch of Proof.** When $T$ is large, to prevent the potential term in the action from diverging, the path must go to $a$ or $b$ and sit near there for intermediate times and then return to $x$. □

The last statement in Theorem 2 also has a path integral proof.

It is a pleasure to thank the organizers of the CBMS Conference on Large Deviations at Southern Illinois University (T. Paine and J. Feinsilver) for a stimulating conference which set me in the right direction, to thank H. Dym and I. Sigal for the hospitality of the Weizmann Institute, where part of this work was done, and C. Fefferman and I. Sigal, for useful conversations.
REFERENCES

1. S. Agmon, On exponential decay of solutions of second order elliptic equations in unbounded domains, Proc. A. Pleijel Conf.
2. ______, Lectures on exponential decay of solutions of second order elliptic equations. Bounds on eigenfunctions of N-body of Schrödinger operators, Math. notes, Princeton Univ. Press, Princeton, N. J., 1980.
3. R. Carmona and B. Simon, Pointwise bounds on eigenfunctions and wave packets in N-body quantum systems. V. Lower bounds and path integrals, Comm. Math. Phys. 80 (1981), 59–98.
4. S. Coleman, The uses of instantons, Proc. Internat. School of Physics, Erice, 1977.
5. S. Combes, P. Duclos and R. Seiler, Krein's formula and one dimensional multiple-well, J. Functional Analysis (to appear).
6. E. Gildener and A. Patrascioiu, Pseudoparticle contributions to the energy spectrum of a one dimensional system, Phys. Rev. D16 (1977), 425–443.
7. E. Harrell, On the rate of asymptotic eigenvalue degeneracy, Comm. Math. Phys. 60 (1978), 73.
8. ______, Double wells, Comm. Math. Phys. 75 (1980), 239.
9. M. Pincus, Gaussian processes and Hammerstein integral equations, Trans. Amer. Math. Soc. 134 (1968), 193–216.
10. M. Schilder, Some asymptotic formulas for Wiener integrals, Trans. Amer. Math. Soc. 125 (1965), 63–85.
11. B. Simon, Functional integration and quantum physics, Academic Press, New York, 1979.
12. ______, Semiclassical analysis of low lying eigenvalues. I. Non-degenerate minima: Asymptotic expansions, Ann. Inst. H. Poincaré (to appear).
13. ______, Semiclassical analysis of low lying eigenvalues. II. Tunneling (in preparation).

DEPARTMENT OF MATHEMATICS AND PHYSICS, CALIFORNIA INSTITUTE OF TECHNOLOGY, PASADENA, CALIFORNIA 91125