A Fulling–Kuchment theorem for the 1D harmonic oscillator

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Abstract
We prove that there exists a pair of non-isospectral 1D semiclassical Schrödinger operators whose spectra agree up to $O(h^\infty)$. In particular, all their semiclassical trace invariants are the same. Our proof is based on an idea of Fulling–Kuchment and Hadamard’s variational formula applied to suitable perturbations of the harmonic oscillator.

1. Introduction

This paper concerns the 1D semiclassical Schrödinger operator
\[ P_V = -\hbar^2 \frac{d^2}{dx^2} + V(x), \quad h > 0, \]
where the real-valued potential $V$ (which is always assumed to be independent of $h$) satisfies
\[ V \in C^\infty(\mathbb{R}), \quad \lim_{|x| \to \infty} V(x) = \infty. \]
For any $h > 0$, the spectrum of $P_V$ on $\mathbb{R}$ is discrete and simple, and we write it as
\[ \text{spec}(P_V) = (\lambda_j)_{j=1}^\infty, \quad \lambda_1 < \lambda_2 < \lambda_3 < \cdots \to \infty. \]
Each $\lambda_j$ depends on $h$, but we do not include this in the notation. We denote by $u_j$ the corresponding eigenfunctions (which also depend on $h$), so that
\[ P_V u_j = \lambda_j u_j, \quad u_j \in L^2(\mathbb{R}). \]

Our main result, which was conjectured by Colin de Verdière in [Col08], is

**Theorem.** There exists a pair of real-valued potentials $V^\pm(x) \in C^\infty(\mathbb{R})$ with $V^\pm(x) \geq 0$ such that the operators
\[ P_V^\pm = -\hbar^2 \frac{d^2}{dx^2} + V^\pm(x) \]
satisfy ‘spec($P_{V^+}$) = spec($P_{V^-}$) up to $O(h^\infty)$’ (so in particular they have the same semiclassical trace invariants) and such that the ground state eigenvalues $\lambda_1^+$ and $\lambda_1^-$ are different for all $h > 0$ except possibly for a sequence $h_k \to 0$. 

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Inverse Problems 28 (2012) 045009
V Guillemin and H Hezari

Here, by ‘spec($P_V$) = spec($P_{V_{-}}$) up to $\mathcal{O}(h^\infty)$’ we mean that for every $E > 0$ and $N > 0$ there exists a constant $C$ such that

$$\sup_{\lambda_j^+ = \lambda_j^-} |\lambda_j^+ - \lambda_j^-| \leq C h^N.$$  (1.2)

The inverse spectral problem for 1D semiclassical Schrödinger operators asks whether spec($P_V$) determines $V$ uniquely up to a translation $x \rightarrow x - x_0$ or reflection $x \rightarrow -x$. The main tools in studying inverse spectral problems are trace invariants such as heat, wave or Schrödinger trace invariants. We recommend the surveys by Zelditch [Zel04], and by Datchev and Hezari [DaHe11] for applications of different kinds of trace formulas in inverse spectral results. However, the theorem above shows the limitations of semiclassical trace invariants meaning that two Schrödinger operators can have the same semiclassical invariants but have different spectra.

An analogous result in the case of bounded plane domains was proved by Fulling and Kuchment in [FuKu05] where they find two bounded plane domains (called Penrose–Lifshits mushrooms) for which all the wave trace invariants agree but the ground state eigenvalues disagree. A Penrose–Lifshits domain $\Omega$ is a semi-ellipse with asymmetrical bumps A, B and C attached to its boundary as in figure 1. If one detaches the bump C, reflects it about the axis of the ellipse and reattaches it, one gets a non-congruent domain $\Omega'$ which has the same heat and wave trace invariants as $\Omega$, i.e. is indistinguishable from $\Omega$ by standard inverse spectral techniques. In [FuKu05], Fulling and Kuchment prove Zelditch’s conjecture (see [Zel04]) that these domains are not isospectral. In [Col08], de Verdière constructs an analog of the Penrose–Lifshits example for the 1D semiclassical Schrödinger operator (see figure 2). Namely, he attaches two small bump functions to the harmonic oscillator potential $V_0(x) = x^2$. By detaching one of these functions, reflecting it about the y-axis and then reattaching it, he is able to construct two non-isomorphic potentials that are isospectral modulo $h^\infty$. Our goal in this paper is to prove a Fulling–Kuchment theorem for this example and verify de Verdière’s conjecture that these ‘isospectral modulo $h^\infty$’ potentials are not isospectral.

To our knowledge, there are no counterexamples to spectral uniqueness of smooth semiclassical Schrödinger operators. There are in fact many recent positive results in this area which use trace invariants but make strong assumptions of analyticity or symmetry on the potential. In [GuUr07], Guillemin and Uribe show that any real analytic potential $V$ on
\(\mathbb{R}^n\), symmetric with respect to all coordinate axes and with a unique global minimum, is determined within the class of all such potentials by the spectrum at the bottom of the well of its semiclassical Schrödinger operator. In [Hez09], Hezari and, in [CoGu08], de Verdière and Guillemin remove the symmetry assumption in dimension 1 but keep the assumption of analyticity (see also [Hez09, GuUr11] for the higher-dimensional case). In [Co08], de Verdière removes both the symmetry and analyticity assumptions in the one-dimensional case, but adds a genericity assumption and uses all eigenvalues instead of only the low lying ones. In [GuWa09], Guillemin and Wang gave a new proof of de Verdière’s result with slightly different generic conditions. In [DaHeVe11], Datchev et al show that radially symmetric potentials in \(\mathbb{R}^n\) are spectrally determined among all smooth potentials.

1.1. Remarks

We close the introduction by listing some remarks and related problems.

- Our method cannot eliminate the possibility of the existence of a sequence \(h_k \to 0\) where the ground state eigenvalues agree. We believe that such a sequence does not exist and we actually expect a much stronger statement to hold.

For all \(j \geq 1\), there exist \(c_j, C_j > 0\): \(|\lambda_j^+ - \lambda_j^-| \geq C_j e^{-c_j/h}\).

- We can also ask the same question for semiclassical resonances. Can we find two smooth compactly supported potentials \(V^+\) and \(V^-\) where \(P_{V^+}\) and \(P_{V^-}\) have distinct resonances which agree up to \(O(h^{\infty})\)? We remind the reader that for a smooth compactly supported real-valued potential \(V\), the resonances of \(P_V\) are the poles of the meromorphic continuation of the resolvent \((P_V - \lambda)^{-1}\).

- It would be interesting to study the analogous problem in the case of compact Riemannian manifolds. To be more precise, can one find a pair of Riemannian manifolds \((M, g)\) and \((M', g')\) where \(\text{spec}(\Delta_g) \neq \text{spec}(\Delta_{g'})\) but all the wave trace invariants are the same, that is, to say \(\text{Tr} e^{-u \sqrt{\Delta_g}} - \text{Tr} e^{-u \sqrt{\Delta_{g'}}} \in C^\infty(\mathbb{R})\)?

2. Proof of theorem

Proof. We will show the existence of the potentials \(V^\pm\) in the theorem by choosing suitable perturbations of the harmonic oscillator \(V_0(x) = x^2\). Suppose \(\alpha, \beta \in C_0^\infty(\mathbb{R})\) are real-valued functions such that \(\text{supp}(\alpha) \subset (-3, -2)\) and \(\text{supp}(\beta) \subset (3, 4)\) and they are not identically zero. We put

\[
V^+(x) = x^2 + t\alpha(x) + \epsilon\beta(x),
V^-(x) = x^2 + t\alpha(x) + \epsilon\beta(-x).
\] (2.1)
We denote by \( \lambda^+_1(\epsilon) \) the ground state eigenvalue of \( P_{\epsilon^+} \). We will show that there exist \( \alpha, \beta \) and \( t, \epsilon > 0 \) small enough such that the pair \( V^\pm \) has the properties asserted in the theorem. From the beginning, we assume that \( \epsilon \) and \( t \) are small enough that \( V^\pm \) do not have any critical points besides \( x = 0 \).

We first show that ‘\( \text{spec}(P_{\epsilon^+}) = \text{spec}(P_{\epsilon^-}) \) up to \( O(h^\infty) \)’ in the sense of (1.2). This is claimed and proved in [Col08] using the method of ‘Bohr–Sommerfeld quantization conditions to all orders’. It can also be proved using quantum Birkhoff normal forms and their equivalence with trace invariants as in [GuWa09]. In that paper, Guillemin and Wang consider the spectral density measure with trace invariants as in [GuWa09].

To show that the ground state eigenvalues \( \lambda^+_1(\epsilon) \) and \( \lambda^-_1(\epsilon) \) are different, we use Hadamard’s variational formula (lemma 2.3 below) which implies that

\[
\frac{d}{d\epsilon} \left|_{\epsilon=0} \lambda^+_1(\epsilon) \right| = \int_{\mathbb{R}} \beta(\pm x)|\psi_1(x)|^2 \, dx,
\]

where \( \psi_1(x) \) is an \( L^2 \) normalized eigenfunction of \(-h^2 \frac{d^2}{dx^2} + x^2 + t\alpha(x)\) with the ground state eigenvalue \( \lambda_1 = \lambda^+_1(0) = \lambda^-_1(0) \). Then, in lemma 2.4 we show that for \( h = 1 \) and \( t \) small enough \( |\psi_1(x)|^2 \) is not an even function in \((-4, -3) \cup (3, 4)\).

This implies that for \( \epsilon \) small enough (and \( t \) small enough), we have

\[
\frac{d}{d\epsilon} \left|_{\epsilon=0} \lambda^+_1(\epsilon) \right| \neq \frac{d}{d\epsilon} \left|_{\epsilon=0} \lambda^-_1(\epsilon) \right|.
\]

This finishes the proof of the theorem. 

Remark 2.1. We note that the Kato–Rellich theorem is very important in our proof. We could not follow our argument with a variable \( h \) because \( \epsilon \) would depend on \( h \). We choose and fix an \( \epsilon \) for \( h = 1 \) and then use the analyticity in \( h \) to argue that except for a sequence \( h_k \rightarrow 0 \), for all \( h > 0 \) we have \( \lambda^+_1(\epsilon) \neq \lambda^-_1(\epsilon) \).
Remark 2.2. We also point out that the eigenvalues $\lambda_1^+(\epsilon)$ are not analytic at $h = 0$. We can see this using the theory of quantum Birkhoff normal forms at the bottom of the well of a potential which was developed by Sjöstrand in [Sj92]. Since $V^\pm(x)$ and $V_0(x) = \lambda^2$ have the same Taylor coefficients at $x = 0$, the bottom of their wells, they have the same QBNFs at $(x, \xi) = (0, 0)$ and therefore the low lying eigenvalues (in particular the ground states) of their Schrödinger operators $P^\pm$ and $P_0$ must have the same asymptotic expansion of the form $q_1 h + q_2 h^2 + \cdots$ as $h \to 0$. However, the ground state eigenvalue of $V_0 = x^2$ is $h$ hence if $\lambda_1^+(\epsilon)$ was analytic at $h = 0$, then we would have $\lambda_1^+(\epsilon) = h$. But this is not the case if for example we choose $\alpha$ and $\beta$ nonnegative and not identically zero. In fact under this assumption we have $\lambda_1^+ > h$. To see this, we recall that

$$\lambda_1^+ = \min_{\phi: \|\phi\|_{L^2} = 1} \left( \left(-h^2 \frac{d^2}{dx^2} + x^2 + \rho(x) \right) \phi, \phi \right)_{L^2}, \tag{2.4}$$

where $\rho = t\alpha + \epsilon \beta$ and by assumption $\rho \geq 0$. Let $u_1$ be an $L^2$ normalized ground state eigenfunction of $-h^2 \frac{d^2}{dx^2} + x^2 + \rho(x)$. Then, in (2.4) the minimum is attained by $u_1$ and

$$\lambda_1^+ = \left( -h^2 \frac{d^2}{dx^2} + x^2 \right) u_1, u_1 \right)_{L^2} + \int \rho |u_1|^2 \, dx.$$

The first term is greater than or equal to $h$ with equality only if $u_1$ is a ground state eigenfunction of the harmonic oscillator in which case the second term is not zero. So $\lambda_1^+ > h$.

We now state Hadamard’s variational formula for Schrödinger operators. It is a formula for the first variation of the eigenvalues of a perturbed operator in terms of the eigenfunctions of the unperturbed operator. Since in this case (unlike, for example, in the case of bounded domains) the argument is simple. We give its proof.

Lemma 2.3. Let $V \in C^\infty(\mathbb{R})$ be real-valued with $\lim_{|x| \to \infty} V(x) = \infty$. Let $\beta \in C^\infty(\mathbb{R})$. Suppose $\lambda_j(\epsilon)$ is the $j$th eigenvalue of $-h^2 \frac{d^2}{dx^2} + V(x) + \epsilon \beta(x)$ and suppose $u_j(x)$ is an $L^2$ normalized eigenfunction of $-h^2 \frac{d^2}{dx^2} + V(x) + \epsilon \beta(x)$ with eigenvalue $\lambda_j(0)$. Then,

$$\frac{d}{d\epsilon} \bigg|_{\epsilon = 0} \lambda_j(\epsilon) = \int_{\mathbb{R}} \beta(x)|u_j(x)|^2 \, dx.$$

Proof. Since in dimension 1 the eigenvalues are simple, for a given $j$ we can choose a smooth one-parameter family $u_j(x, \epsilon)$ of $L^2$ normalized real eigenfunctions of $-h^2 \frac{d^2}{dx^2} + V(x) + \epsilon \beta(x)$ with eigenvalues $\lambda_j(\epsilon)$. So by our notation $u_j(x) = u_j(x, 0)$. We now write

$$\frac{d}{d\epsilon} \bigg|_{\epsilon = 0} \lambda_j(\epsilon) = \frac{d}{d\epsilon} \bigg|_{\epsilon = 0} \left( -h^2 \frac{d^2}{dx^2} + V(x) + \epsilon \beta(x) \right) u_j(x, \epsilon), u_j(x, \epsilon) \right)_{L^2} = \left( \beta(x) u_j(x), u_j(x) \right)_{L^2} + \left( -h^2 \frac{d^2}{dx^2} + V(x) \left. \frac{d}{d\epsilon} \right|_{\epsilon = 0} u_j(x, \epsilon), u_j(x) \right)_{L^2} + \left( -h^2 \frac{d^2}{dx^2} + V(x) \right) u_j(x), \frac{d}{d\epsilon} \bigg|_{\epsilon = 0} u_j(x, \epsilon) \right)_{L^2}.$$

Because $V$ is real valued, the operator $-h^2 \frac{d^2}{dx^2} + V(x)$ is symmetric and therefore the last two terms are identical. In fact, each one is zero. This follows from $\left( u_j(x), \left. \frac{d}{d\epsilon} \right|_{\epsilon = 0} u_j(x, \epsilon) \right)_{L^2} = 0$ which in turn follows by applying $\left. \frac{d}{d\epsilon} \right|_{\epsilon = 0}$ to the equation $(u_j(x, \epsilon), u_j(x, \epsilon))_{L^2} = 1$. □

In the next lemma, we put $h = 1$. 

5
Inverse Problems 28 (2012) 045009

V Guillemin and H Hezari

Lemma 2.4. Let \( \alpha \in C_0^\infty ((-3, -2)) \) be nonnegative and not identically zero and let \( V(x) = x^2 + t\alpha(x) \). Suppose \( u_1(x) \) is a ground state eigenfunction of \(-\frac{d^2}{dx^2} + V(x)\) with the ground state eigenvalue \( \lambda_1 \). Then, there exists \( t > 0 \) small enough such that \( |u_1(x)|^2 \) is not an even function on \((-4, -3) \cup (3, 4)\).

Proof. First of all since away from \( \text{supp}(\alpha) \) the potential \( V(x) \) is real analytic, if \( |u_1(x)|^2 \) is even on \((-4, -3) \cup (3, 4)\) then by analytic continuation it is even on \((-\infty, -3) \cup (3, \infty)\). We also note that \((u_1(x))^2\) being even implies that \( u_1(x) \) is even. This is because a ground state eigenfunction never vanishes. Therefore, \( u_1(x) \) cannot change sign and in particular cannot be odd anywhere.

To prove \( u_1(x) \) is not even on \((-\infty, -3) \cup (3, \infty)\), we introduce the parabolic cylinder functions below and review some of their basic properties in section 3.

Let \( W(x) \) be the unique solution to
\[
-W''(x) + (x^2 - \lambda_1)W(x) = 0,
\]
with
\[
\lim_{x \to -\infty} W(x) = 0 \quad \text{and} \quad W(-3) = u_1(-3).
\]
The function \( W(x) \) is called a Weber function. An argument using (2.4), similar to that in remark 2.2, shows that for \( t \) small enough, we have \( 1 < \lambda_1 < 3 \). In fact, we can make \( \lambda_1 \) arbitrary close to 1. By the WKB method, we see that \(|W(x)|\) either grows or decays exponentially as \( x \to \infty \), but exponential decay is ruled out by the fact that it would make \( W \) an eigenfunction of the harmonic oscillator with eigenvalue \( \lambda_1 \neq \{1, 3, 5, \ldots\} \). Thus, \( W(x) \) is exponentially decaying near \( -\infty \) with \( \lim_{x \to -\infty} W = 0 \) and exponentially growing (in absolute value) near \( \infty \). In fact, we will see in section 3 that \( \lim_{x \to \infty} W = -\infty \), and that \( W \) has a unique critical point (which is a global maximum) at \( x = -a, |a| < \sqrt{\lambda_1} \), and vanishes only once for a large positive value of \( x \). In particular, \( W'(x) \) is positive for \( x < -a \) and negative for \( x > -a \). See figure 3 for a graph of \( W \). We will prove these claims about \( W \) in section 3.

Since \( u_1 \) satisfies the same equation as \( W \) on \((-\infty, -3) \cup (-2, \infty)\), using \( u(-3) = W(-3) \) we have
\[
u_1(x) = W(x), \quad x \leq -3,
\]
and using \( \lim_{t \to \pm \infty} u_1(t) = \lim_{t \to \pm \infty} W(-x) = 0 \) we have

\[
u_1(x) = cW(-x), \quad x \geq -2
\]

for a positive constant \( c \). In particular, \( u_1(0) = cW(0) \). We claim that \( c > 1 \) which will show that \( u_1 \) is not even on \((-\infty, -3) \cup (3, \infty)\), completing the proof of the lemma.

The proof that \( c > 1 \) uses Sturm–Liouville theory. Let \( Q(x) = \lambda_1 - x^2 \) and \( Q_1(x) = \lambda_1 - x^2 - t\alpha(x) \). Then,

\[
W'' + QW = 0, \quad \text{(2.6)}
\]

and

\[
u_1'' + Q_1u_1 = 0. \quad \text{(2.7)}
\]

We rewrite (2.6) and (2.7) as a first-order system using the Prüfer substitution:

\[
\begin{cases}
(x) = r(x) \sin \theta(x) \\
W'(x) = r(x) \cos \theta(x),
\end{cases} \quad \begin{cases}
u_1(x) = r_1(x) \sin \theta_1(x) \\
\nu_1'(x) = r_1(x) \cos \theta_1(x),
\end{cases}
\]

where we choose the branches of \( \theta \) and \( \theta_1 \) such that \( \theta(-3) = \theta_1(-3) \in (0, \pi/2) \) (this is possible because \( W(-3) > 0 \) and \( W'(-3) > 0 \), see section 3). Then (see [BirRot] section 5, chapter 10),

\[
\begin{align*}
\theta'(x) &= Q(x) \sin^2 \theta(x) + \cos^2 \theta(x), \\
\theta_1'(x) &= Q_1(x) \sin^2 \theta_1(x) + \cos^2 \theta_1(x),
\end{align*}
\]

and by (2.8)

\[
\begin{align*}
W'(x) &= \cot \theta(x)W(x), \\
\nu_1'(x) &= \cot \theta_1(x)u_1(x).
\end{align*}
\]

Because \( Q_1(x) \leq Q(x) \) and because \( \theta_1(-3) = \theta(-3) \), by applying an elementary comparison theorem to (2.9) (see [BirRot, theorem 7, chapter 1]), we get

\[
\theta_1(x) \leq \theta(x) \quad \text{for} \quad x \geq -3. \quad \text{(2.11)}
\]

Moreover, since \( W(x) \) and \( W'(x) \) are positive on \( x < -a \) (see section 3) we have \( 0 < \theta(x) < \frac{\pi}{2} \) for \( x < -a \) and thus \( \theta_1(x) < \frac{\pi}{2} \) for \( -3 \leq x < -a \). In fact, because \( u_1 \) never vanishes, \( \theta_1(x) \) is never zero and

\[
0 < \theta_1(x) \leq \frac{\pi}{2} \quad \text{for} \quad -3 \leq x < -a.
\]

Using this and (2.11), by applying an elementary comparison theorem to (2.10) and because \( u_1(-3) = W(-3) \), we obtain

\[
u_1(x) \geq W(x) \quad \text{for} \quad -3 \leq x \leq -a. \quad \text{(2.12)}
\]

This is the key point: (2.12) is an inequality for \( u_1 \) and \( W \) in the region where they solve different equations. On the other hand, \( u_1(x) = cW(-x) \) for \( x \geq -2 \) so

\[
u_1'(x) = -cW'(-x) \quad \text{for} \quad x \geq -2, \quad \text{(2.13)}
\]

and in particular \( u_1'(-a) = -cW'(-a) \). If \( \theta_1(-a) = \frac{\pi}{2} \), then \( u_1'(-a) = 0 \) by (2.8) and therefore \( W'(a) = 0 \). But \( W \) has only one critical point which is at \( x = -a \). Hence, \( \theta_1(-a) < \frac{\pi}{2} \). Then, by (2.8) \( u_1'(-a) > 0 \) and thus \( W'(a) < 0 \). This shows that \( a \) must be positive because if \( a < 0 \) then the point \( a \) is on the left of the critical point \(-a\) of \( W \) but \( W \) is increasing for \( x < -a \). Finally, \( W \) is decreasing on \((-a, 0) \) and by (2.13) \( u_1 \) is increasing on \((-a, 0) \). So by (2.12) \( u_1(0) > W(0) \) and therefore \( c > 1 \).
3. Parabolic cylinder functions (Weber functions) with small frequency

Let $W(x)$ be a Weber function with small frequency which was defined in (2.5). Here we prove the properties of $W$ which are needed in the proof of lemma 2.4.

That $W(x)$ decays exponentially near $-\infty$ and grows exponentially near $\infty$ follows from the classical WKB method for ODEs (see, for example, [Ol]). In fact the exact decay and growth rates (see [WhiWa], section 16.5) are given by

$$W(x) \sim C(\sqrt{2|x|})^{(\lambda_1-1)/2} e^{-x^2/2} \quad \text{as } x \to -\infty,$$

$$W(x) \sim \frac{C\sqrt{2\pi}}{\Gamma(\frac{1}{2}(1-\lambda_1))} (\sqrt{2x})^{-(\lambda_1+1)/2} e^{x^2/2} \quad \text{as } x \to \infty,$$

where $C$ is a positive constant which depends on our normalization $W(-3) = u_1(-3)$.

Note that for $\lambda_1 > 1$ very close to 1 we have $\Gamma(\frac{1}{2}(1-\lambda_1)) < 0$ which shows that $\lim_{x \to -\infty} W(x) = -\infty$.

To prove the other properties of $W$, we first show that $W$ is positive on $(-\infty, 3]$. To do this, we choose $\eta \in C_0^\infty(3, 4)$ nonnegative and consider the operator

$$-\frac{d^2}{dx^2} + x^2 + \delta \eta(x).$$

We represent its ground state eigenvalue by $\mu_1(\delta)$ and an associated smooth family of $L^2$ normalized eigenfunctions by $\psi_1(x, \delta)$. Then, by Hadamard’s variational formula

$$\frac{d}{d\delta} \mu_1(\delta) = \int \eta(x) |\psi_1(x, \delta)|^2 dx.$$

Similarly

$$\frac{d}{dt} \lambda_1(t) = \int \alpha(x) |u_1(x, t)|^2 dx.$$

This implies that $\mu_1(\delta)$ and $\lambda_1(t)$ are increasing functions in $\delta$ and $t$, respectively. Thus, because $\mu_1(0) = \lambda_1(0) = 1$, we can find $\delta$ and $t$ positive so that $1 < \mu_1(\delta) = \lambda_1(t) < 2$. This is the value $t$ that we choose in lemma 2.4. Because $\psi_1$ satisfies the same equation as $W$ for $x \leq 3$ we have $\psi_1 = kW$ on $(-\infty, 3]$. On the other hand, since $\psi_1$ is a ground state eigenfunction it does not vanish on $\mathbb{R}$ so the Weber function $W$ has no zeros in $(-\infty, 3]$ and must be positive there.

We can use this fact to show that there is only one critical point which is at the maximum $x = -a$. First of all, in the forbidden region $x < -\sqrt{A}$ we have $W(x) > 0$ and therefore by (2.5) we have $W'' > 0$ there. This implies that $W'$ will increase on $(-\infty, -\sqrt{A})$ and in particular will never vanish. The maximum $x = -a$ must be in the classical region $|x| \leq \sqrt{A}$ where $W''$ and $W$ have different signs. There cannot be two critical points in the classical region because then by Rolle’s theorem $W''$ would vanish in between them, and $W$ would vanish there as well by the equation, contradicting $W > 0$. Furthermore, $W$ cannot have any critical points in the forbidden region $x > \sqrt{A}$. Assume $x_0$ is such a critical point. Then, $W''(x_0) \neq 0$ because if it were zero then by (2.5) $W(x_0) = 0$ which together with would $W''(x_0) = 0$ would imply that $W$ is a trivial solution. If $W''(x_0) > 0$ then by (2.5) $W(x_0) > 0$ and the graph of $W$ should stay concave up for all $x > x_0$ which implies that $\lim_{x \to \infty} W(x) = \infty$ which is a contradiction. Finally, if $W''(x_0) < 0$ then $W(x_0) < 0$ but because $W(3) > 0$ we should have a zero of $W$ between 3 and $x_0$ which shows that $x_0 > 3$. Now if $z_0$ is the smallest zero with $z_0 > 3$, then $W'(z_0) < 0$. After this point $z_0$, $W'$ can only decrease (and is never zero) because $W'' < 0$ in this region. This contradicts $W''(z_0) = 0$.

This concludes the proof of the properties of $W$ which are needed for lemma 2.4. In the course of the proof of this lemma, we also prove that $a > 0$. 


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