Large supremum norms and small Shannon entropy for Hecke eigenfunctions of quantized cat maps

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Abstract

This paper concerns the behavior of eigenfunctions of quantized cat maps and in particular their supremum norm. We observe that for composite integer values of N, the inverse of Planck's constant, some of the desymmetrized eigenfunctions have very small support and hence very large supremum norm. We also prove an entropy estimate and show that our functions satisfy equality in this estimate. In the case when N is a prime power with even exponent we calculate the supremum norm for a large proportion of all desymmetrized eigenfunctions and we find that for a given N there is essentially at most four different values these assume.

1 Introduction

A well studied model in quantum chaos is the so called quantized cat map - a "quantized version" of the dynamical system given by a hyperbolic (i.e. with $|\operatorname{tr}(A)| > 2$) matrix $A \in SL(2, \mathbb{Z})$ acting on the two dimensional torus. The quantization of these systems is a unitary operator $U_N(A)$ acting on the space $L^2(\mathbb{Z}_N) \cong \mathbb{C}^N$. This model was first introduced by Berry and Hannay [7] and has been developed in a number of papers [10, 4, 5, 9, 21, 12, 6, 15]. The general idea is that the chaotic behavior of the classical system corresponds to eigenfunctions of the quantized system being "nicely spread out" in the so called semiclassical limit, that is, when N goes to infinity. $U_N(A)$ can have large degeneracies, but as Kurlberg and Rudnick explained in [12], this is a consequence of quantum symmetries in our model. Namely, there is a large abelian group of unitary operators commuting with $U_N(A)$. In analogy with the theory of modular forms, these operators are called Hecke operators and their joint eigenfunctions are called Hecke eigenfunctions. Kurlberg and Rudnick showed that the Hecke eigenfunctions become uniformly distributed as $N \to \infty$, a fact often referred to as arithmetic quantum unique ergodicity (QUE) for cat maps.

Another natural question relating to eigenfunctions "spreading out" in the limit is the question of estimating their supremum norms. Given the matrix

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A, the primes (all but a finite number of them to be exact) can be divided in two parts called split and inert, and in [13] and [11] it was shown that for such prime numbers N the supremum norm of L^2-normalized Hecke eigenfunctions are bounded by $2/\sqrt{1-1/N}$ and $2/\sqrt{1+1/N}$ respectively. As an immediate consequence of this it follows that as long as N is square free, all Hecke eigenfunctions ψ fulfill $\|\psi\|_\infty = O(N^\epsilon)$ for all $\epsilon > 0$. For general N we only know that the supremum is $O_\epsilon\left(N^{3/8+\epsilon}\right)$ for all $\epsilon > 0$ (cf. [13]). In view of the results for prime numbers N and the quantum unique ergodicity, one might think that all Hecke eigenfunctions have small supremum norm, maybe even smaller than N^ϵ for all $\epsilon > 0$, however this is not the case. In this paper we observe that, unless N is square free, some of the Hecke eigenfunctions are localized on ideals of $\mathbb{Z}_N$ and for such functions we get rather large supremum norms. To be more precise, if $N = a^2$ we can find an eigenfunction with supremum norm $\gg N^{1/4}$. This result is somewhat analogous with the result of Rudnick and Sarnak [17] concerning the supremum norm of eigenfunctions of the Laplacian of a special class of arithmetic compact 3-manifolds. They show that the supremum of some so called "theta lifts" are $\gg \lambda^{1/4}$, where λ is the corresponding eigenvalue. For a L^2-normalized function in $L^2(\mathbb{Z}_N)$ it is trivial to see that the maximal supremum is $N^{1/2}$ and the (sharp) general upper bound for the supremum of an eigenfunction of the Laplacian of a compact manifold is $O\left(\lambda^{(d-1)/4}\right)$, where d is the dimension of the manifold (cf. [19]). For $d = 3$, we see that the growth we obtain for our eigenfunctions is analogous to the growth of the "theta lifts" in the sense that they are both the square root of the largest possible growth.

In Theorem 3.3 we note that the action of U_N on the subspace spanned by the Hecke eigenfunctions localized on ideal is isomorphic to the action of $U_{N'}$ on $L^2(\mathbb{Z}_{N'})$ for some $N'|N$. This means that one can think of these eigenfunctions as the analogue of what in the theory of automorphic forms is called oldforms. Hecke eigenfunctions that are orthogonal to the oldforms play the role of newforms. Note that the existence of oldforms, although their supremum is large, has small relation to the concept of scarring. On the one hand we know from the result of Kurlberg and Rudnick that no scarring is possible for Hecke eigenfunctions, and on the other hand the ideals themselves equidistribute, hence it is not surprising that oldforms do not contribute to scars.

Another quantity one can study in order to determine how well eigenfunctions "spread out" is the Shannon entropy, a large entropy signifies a well-spread function. This has been done in a recent paper by Anantharaman and Nonnenmacher [2] for the baker's map. In this study they use estimates from below of the Shannon entropy to show that the Kolmogorov-Sinai entropy of the induced limit measures (so called semiclassical measures) is always at least half of the Kolmogorov-Sinai entropy of the Lebesgue measure. We prove that the equivalent estimate of the Shannon entropies is true for eigenfunctions of the quantized cat map and that our large eigenfunctions makes this estimate sharp. Even though the Hecke eigenfunctions do not contribute to scars (which other sequences of eigenfunctions do) they are still as badly spread out as possible in the sense of entropy. That is, even though the only limiting measure of Hecke functions is the Lebesgue measure and this has *maximal* Kolmogorov-Sinai entropy, some of the Hecke functions have *minimal* Shannon entropy.

In the study of newforms a very surprising phenomena occurs; assume for simplicity that $N = p^k$ with $k > 1$, then it seems like the space is divided into two or four different subspaces and Hecke eigenfunctions in the same space have the

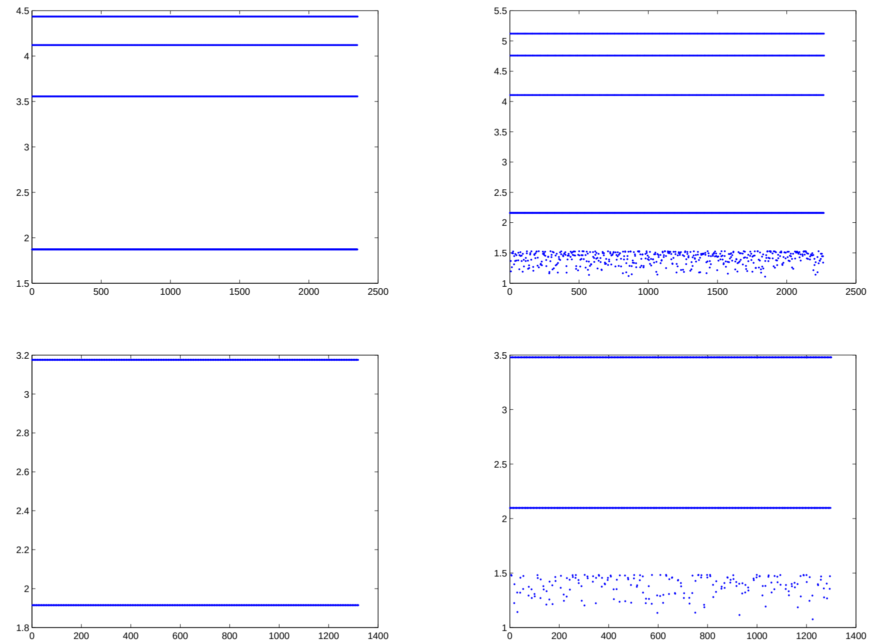

Figure 1: The supremum norm of all the newforms of a given matrix A (one matrix A for each picture): in the upper row $N = 7^4$ and in the lower $N = 11^3$ and in the left column the primes (i.e. $7, 11$) are inert, while in the right column, they are split. The newforms are ordered with respect to growing phase (in the interval $[-\pi, \pi)$) of their eigenvalues, when these are evaluated at some specific element of maximal order in the Hecke algebra.

same or almost the same supremum norm. These norms are not dependent on A other than that the normalization factor is different if A makes p split or inert. We will derive these properties in the case where the power of p is even. This is done using an arithmetic description of the Hecke eigenfunctions introducing two parameters C and D where the different lines corresponds to the solvability of second and third order equations of CD modulo p. Moreover, the exact values these supremum norms are calculated. The lower line is not a true line but rather a strip of width $O(N^{-1})$ just below the value $2/\sqrt{1 \pm 1/p}$ corresponding to p being split or inert. This is the same value as the known bound for primes N. The other lines are true lines and their values are calculated in Theorem 7.2, the values are of the size $N^{1/6}$. The “noise” we see for the split case is also explained and corresponds to $p|C$. As we see in figure 1, numerical simulations suggests that similar properties hold also for odd powers of p. Actually the techniques we develop in Chapter 5 for even exponents can be modified and used for odd exponents, but this take some effort and will be explored in a forthcoming paper.

Our calculations show that if $N = p^{2k}$ ($p > 3$ and p is either split or inert) then the supremum of all Hecke eigenfunctions is bounded by $N^{1/4}$ and this estimate is sharp. By multiplicativity this is then true for all products of such N.

2 Short description of the model

This will be a very brief introduction to quantized cat maps, more or less just introducing the notation we will use. A more extensive setup can be found in [12].

Take a matrix $A \in SL(2,\mathbb{Z})$. We assume that $|\operatorname{tr}(A)| > 2$ to make the system chaotic and that the diagonal entries of A are odd and the off diagonal are even. If N is even we make the further assumption that $A \equiv I \pmod 4$. These congruence assumptions are needed in order for the quantization of the dynamics to be consistent with the quantization of observables. In each time step we map $x \in \mathbb{T}^2 \cong \mathbb{R}^2/\mathbb{Z}^2$ to $Ax \in \mathbb{T}^2$ and observables $f \in C^\infty(\mathbb{T}^2)$ are sent to $f \circ A$. Note that the assumptions above not will affect the quantization for a fixed odd N following below. For instance the fact that A is hyperbolic does not say anything about its image in $SL(2,\mathbb{Z}_N)$ for a fixed N and therefore all Theorems in the article are true without this assumption. Our aim in the end is however of course to fix A and let N grow and then the fact that A is hyperbolic will tell us a lot about the different images of A in $SL(2,\mathbb{Z}_N)$. If N is a prime and N is large enough then A will not be upper triangular for example.

The quantization of the dynamics is a unitary operator $U_N(A)$ acting on "the state space" $L^2(\mathbb{Z}_N)$, equipped with the inner product

$$< \phi, \psi >= \frac{1}{N} \sum_{Q \in \mathbb{Z}_N} \phi(Q)\overline{\psi(Q)}.$$

Assume for a moment that we know how to define $U_N(A)$ when N is a prime power. For general N we write $N = p_1^{\alpha_1}...p_m^{\alpha_m}$ and via the Chinese remainder theorem we get an isomorphism between $L^2(\mathbb{Z}_N)$ and $\bigotimes_{j=1}^m L^2\left(\mathbb{Z}_{p_j^{\alpha_j}}\right)$. Using this decomposition we define $U_N(A) := \otimes_{j=1}^m U_{p_j^{\alpha_j}}(A)$. We now only have to define $U_{p^k}(A)$ and for odd p this is done in the following manner: Identify A with its image in $SL(2,\mathbb{Z}_{p^k})$ and use the Weil representation to quantize A. This is a representation of $SL(2,\mathbb{Z}_{p^k})$ on $L^2(\mathbb{Z}_{p^k})$, which for odd primes p is given on the generators by

$$U_{p^k}(n_b)\psi(x) = e\left(\frac{rbx^2}{p^k}\right)\psi(x) \tag{1}$$

$$U_{p^k}(a_t)\psi(x) = \Lambda(t)\psi(tx) \tag{2}$$

$$U_{p^k}(\omega)\psi(x) = \frac{S_r(-1,p^k)}{\sqrt{p^k}} \sum_{y \in \mathbb{Z}_{p^k}} \psi(y) e\left(\frac{2rxy}{p^k}\right), \tag{3}$$

where we have introduced the notation

$$n_b = \begin{pmatrix} 1 & b \\ 0 & 1 \end{pmatrix}, \quad a_t = \begin{pmatrix} t & 0 \\ 0 & t^{-1} \end{pmatrix}, \quad \omega = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \text{ and } e(x) = e^{i2\pi x}.$$

($\Lambda(t)$ and $S_r(-1,p^k)$ are numbers with absolute value 1 and r is a specific unit in $\mathbb{Z}_N$, see [12] for details.) For $p = 2$ the construction is similar but not quite the same: A should be identified with its image in $SL(2,\mathbb{Z}_{2^{k+1}})$ and the representation should only be defined on the subgroup of all matrices congruent to the identity modulo 4 in $SL\left(2, \mathbb{Z}_{2^{k+1}}\right)$. This subgroup is generated by a_t, n_b, n_c^T (where $t \equiv 1 \pmod 4$ and $b \equiv c \equiv 0 \pmod 4$) and

$$U_{2^k}(a_t)\psi(x) = \Lambda(t)\psi(tx) \tag{4}$$

$$U_{2^k}(n_b)\psi(x) = e\left(\frac{rbx^2}{2^{k+1}}\right)\psi(x) \tag{5}$$

$$U_{2^k}(n_c^T) = H^{-1}U_{2^k}(n_{-c})H, \tag{6}$$

where

$$H\psi(x) = \frac{1}{\sqrt{2^k}} \sum_{y \in \mathbb{Z}_{2^k}} \psi(y) e\left(\frac{rxy}{2^k}\right). \tag{7}$$

Remark. There is miss print in the definition of $U_{2^k}(n_c^T)$ in [12]; the expression in that definition should be divided by 2 to give a correct definition.

The Hecke operators corresponding to the matrix A are all the operators written as $U_N(g)$, where $g = xI + yA$ and g has determinant congruent to 1 modulo N.

3 Hecke eigenfunctions with large supremum norm

Definition 3.1. For $k \geqslant m \geqslant n$ we let

$$S_k(m,n) = \left\{ f \in L^2\left(\mathbb{Z}_{p^k}\right); p^m | x - y \Rightarrow f(x) = f(y) \quad \wedge \quad p^n \nmid x \Rightarrow f(x) = 0 \right\}.$$

Remark. $S_k(m,n)$ can be canonically embedded into $L^2\left(\mathbb{Q}_p\right)$. As functions of the p-adic numbers these functions are called Schwartz functions because of their analogy with the Schwartz functions of a real variable.

Theorem 3.1. *Let p be an odd prime and $m \leqslant k \leqslant 2m$. Then $S_k(m, k-m)$ is invariant under the action of U_{p^k}.*

Proof. Let $f \in S_k(m, k-m)$. It is easy to see that $U_{p^k}(a_t)f \in S_k(m, k-m)$ and that $U_{p^k}(n_b)f(x) = 0$ if $p^{k-m} \nmid x$. Moreover we have

$$\begin{aligned} U_{p^k}(n_b)f\left(p^{k-m}x + yp^m\right) &= e\left(\frac{rb\left(p^{k-m}\left(x + yp^{2m-k}\right)\right)^2}{p^k}\right) f\left(p^{k-m}x + yp^m\right) \\ &= e\left(\frac{rb\left(x + yp^{2m-k}\right)^2}{p^{2m-k}}\right) f\left(p^{k-m}x\right) \\ &= e\left(\frac{rbx^2}{p^{2m-k}}\right) f\left(p^{k-m}x\right) = U_{p^k}(n_b)f\left(p^{k-m}x\right) \end{aligned}$$

and

$$
\begin{aligned}
U_{p^k}(\omega)f(x) =& \frac{S_r\left(-1,p^k\right)}{\sqrt{p^k}} \sum_{y\in\mathbb{Z}_{p^k}} f(y)e\left(\frac{2rxy}{p^k}\right) \\
=& \frac{S_r\left(-1,p^k\right)}{\sqrt{p^k}} \sum_{y\in\mathbb{Z}_{p^m}} f\left(yp^{k-m}\right)e\left(\frac{2rxy}{p^m}\right) \\
=& \frac{S_r\left(-1,p^k\right)}{\sqrt{p^k}} \sum_{a\in\mathbb{Z}_{p^{2m-k}}} \sum_{b\in\mathbb{Z}_{p^{k-m}}} f\left(\left(a+p^{2m-k}b\right)p^{k-m}\right) \\
& e\left(\frac{2rx\left(a+p^{2m-k}b\right)}{p^m}\right) \\
=& \frac{S_r\left(-1,p^k\right)}{\sqrt{p^k}} \sum_{a\in\mathbb{Z}_{p^{2m-k}}} f\left(ap^{k-m}\right)e\left(\frac{2rxa}{p^m}\right) \sum_{b\in\mathbb{Z}_{p^{k-m}}} e\left(\frac{2rxb}{p^{k-m}}\right).
\end{aligned}
$$

If $p^{k-m} \nmid x$ then the sum over b is equal to zero, and the sum over a only depends on the remainder of x modulo p^m. Thus $U_{p^k}(\omega)f \in S_k(m,k-m)$ which concludes the proof. □

Theorem 3.2. *Let $N = p^k$, where p is an odd prime. Then there exists Hecke eigenfunctions $\psi \in L^2(\mathbb{Z}_N)$ such that $\|\psi\|_2 = 1$ and*

$$\|\psi\|_\infty \geqslant p^{\left[\frac{k}{2}\right]/2}.$$

Proof. The Hecke operators are of the form $U_{p^k}(B)$ for $B \in SL(2,\mathbb{Z})$ where all B commute. Since $S_k(k-[k/2],[k/2])$ is $SL(2,\mathbb{Z})$-invariant there must be a joint eigenfunction ψ of all $U_{p^k}(B)$ such that $\psi \in S_k(k-[k/2],[k/2])$. If this function is normalized to have $\|\psi\|_2 = 1$, we get that

$$\frac{p^{k-[k/2]}}{p^k}\|\psi\|_\infty^2 \geqslant \|\psi\|_2^2 = 1$$

by the estimation $|\psi(x)| \leqslant \|\psi\|_\infty$ on the support of ψ. □

When k is even the space $S_k(k-[k/2],[k/2]) = S_k(k/2,k/2) = \mathbb{C}f$ where

$$f(x) = \begin{cases} 1 & \text{if } p^{k/2}|x \\ 0 & \text{else} \end{cases} \tag{8}$$

and we have $U_{p^k}(A)f = f$ for all $A \in SL(2,\mathbb{Z})$.

Remark. Even though this observation seem to be almost unknown before (and was to me), Nonnenmacher finds a state equivalent to (8) in [16]. He also seem to understand the structure given in Theorem 3.3 although his presentation is less formal.

The action of the Weil representation on $S_k(k-m,m)$ is isomorphic to the action on the full space, but for a different N. More precisely, let T_m : $S_k(k-m,m) \to L^2\left(\mathbb{Z}_{p^{k-2m}}\right)$ be defined by $(T_m\psi)(x) = p^{-m/2}\psi(p^m x)$, then T_m is a bijective intertwining operator. In other words:

Theorem 3.3. *Let $N = p^k$, where p is an odd prime. The operators T_m are bijective and if $\psi \in S_k(k-m, m)$ we have that $U_{p^k}(A)\psi = T_m^{-1} U_{p^{k-2m}}(A) T_m \psi$.*

Proof. That T_m is well defined and bijective is trivial. We are left with proving that the identity holds for the generators of $SL(2, \mathbb{Z}_{p^k})$. This is immediate for n_b and a_t and for ω we have

$$\begin{aligned}(T_m U_{p^k}(\omega)\psi)(x) &= \frac{S_r\left(-1, p^k\right)}{\sqrt{p^{k+m}}} \sum_{y \in \mathbb{Z}_{p^k}} \psi(y) e\left(\frac{2rxy}{p^{k-m}}\right) \\ &= \frac{S_r\left(-1, p^{k-2m}\right)}{\sqrt{p^{k-m}}} \sum_{y \in \mathbb{Z}_{p^{k-m}}} \psi(y) e\left(\frac{2rxy}{p^{k-m}}\right) \\ &= \frac{S_r\left(-1, p^{k-2m}\right)}{\sqrt{p^{k-2m}}} \sum_{y \in \mathbb{Z}_{p^{k-2m}}} p^{-m/2} \psi(p^m y) e\left(\frac{2rxy}{p^{k-2m}}\right) \\ &= (U_{p^{k-2m}}(\omega) T_m \psi)(x).\end{aligned}$$

□

Remark. T_m is in fact unitary.

One can obtain results analogous to Theorem 3.1 and Theorem 3.2 for $p = 2$.

Theorem 3.4. *Let $p = 2$ and $m \leqslant k \leqslant 2m + 1$. Then $S_k(m, k-1-m)$ is invariant under the action of U_{2^k}.*

Proof. Observe that we only need to show that $S_k(m, k-1-m)$ is preserved by (4), (5) and (7) and do the same calculations as in the proof of Theorem 3.1. □

Corollary 3.5. *Assume that $N = ab^2$, where b is odd, or that $N = 2ab^2$. Then, in both situations, there exists normalized Hecke eigenfunctions $\psi \in L^2(\mathbb{Z}_N)$ such that*

$$\|\psi\|_\infty \geqslant b^{1/2}.$$

Proof. Follows immediately from Theorem 3.2 and Theorem 3.4 since $\|f \otimes g\|_\infty = \|f\|_\infty \|g\|_\infty$. □

4 Shannon entropies of Hecke functions

Entropy is a classical measure of uncertainty (chaos) in a dynamical system and recently this has been studied in a number of papers in the context of quantum chaos, see [2],[1]. The main conjecture can intuitively be described in the following way: The entropy is always at least half of the largest possible entropy.

Definition 4.1. Let $f \in L^2(\mathbb{Z}_N)$ and assume $\|f\|_2 = 1$. We define the Shannon entropy to be

$$h(f) = -\sum_{x \in \mathbb{Z}_N} \frac{|f(x)|^2}{N} \log \frac{|f(x)|^2}{N}.$$

In [2], Anantharaman and Nonnenmacher prove the described conjecture in the case of semiclassical limits of the Walsh-quantized baker's map with $N = D^k$ and D fixed. In the course of this proof they come across similar inequalities for the Shannon entropy of the specific eigenstates. The maximal entropy is trivially $\log N$ (as it is for our eigenfunctions) and they show that each eigenstate ψ_N fulfills

$$h(\psi_N) \geqslant \frac{1}{2}\log N. \tag{9}$$

In view of this it is natural to ask the question if (9) hold also for Hecke eigenfunctions, or more generally, for eigenfunctions of $U_N(A)$. Let us first note that if we for instance take N to be prime and put $A = n_b$ for some $b \neq 0$ then the function

$$f(x) = \begin{cases} \sqrt{N} & \text{if } x = 0 \\ 0 & \text{else} \end{cases}$$

fulfills $U_N(A)f = f$ and $h(f) = 0$, hence the inequality in (9) can not be true in full generality. However the following is true:

Theorem 4.1. *Assume that A is not upper triangular modulo p for any $p|N$. If $f \in L^2(\mathbb{Z}_N)$ is a normalized eigenfunction of $U_N(A)$ then $h(f) \geqslant \frac{1}{2}\log N$.*

If f is the function defined in (8) then $N^{1/4}f = p^{k/4}f$ fulfills $h(f) = 1/2\log N$, hence the inequality in Theorem 4.1 is sharp. The proof of the Theorem is a simple application of an Entropic Uncertainty Principle, which can be found in [2]. The Entropic Uncertainty Principle was first proved by Maassen and Uffink [14], but they formulated the relation in a slightly different manner.

Theorem 4.2. Entropic Uncertainty Principle *Let N be a positive integer and let U be a unitary $N \times N$ matrix. If we denote $c(U) = \max |U_{i,j}|$, then*

$$h(f) + h(Uf) \geqslant -2\log c(U)$$

for all $f \in L^2(\mathbb{Z}_N)$ with $\|f\|_2 = 1$.

Proof of Theorem 4.1. It is enough to prove the statement for $N = p^k$. Let $A = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$. Since $p \nmid c$ we can write $A = n_{b_1}\omega n_{b_2}a_t$ where $t = -c$, $b_1 = ac^{-1}$ and $b_2 = cd$. Inserting this into the definition of U_N we get

$$U_N(A)\psi(x) = \frac{S_r(-1,N)}{\sqrt{N}}\Lambda(t)\sum_{y\in\mathbb{Z}_N} e\left(\frac{r\left(b_1x^2 + b_2y^2 + 2xy\right)}{N}\right)\psi(ty).$$

Hence, if we view $U_N(A)$ as an $N \times N$ matrix then all its entries have absolute value $N^{-1/2}$ and thus if $U_N(A)f = \lambda f$ then the Entropic Uncertainty Principle says that $h(f) = h(U_N(A)f) \geqslant -\log N^{-1/2} = 1/2\log N$. $\square$

Note that the function defined in (8) is invariant under the action of $SL(2,\mathbb{Z}_N)$ and in particular if we apply the Fourier transform to it. Thus the Shannon entropy of the state is trivially the same in both the "position"-representation and the "momentum"-representation. Eigenfunctions with this property was also observed by Anantharaman and Nonnenmacher in their study of the baker's map, however there is a big difference between the two quantizations and therefore what entropy tells us about the system. The baker's map is quantized in a manner where different states in a natural way is related to a probability measure of the torus. This is done through the introduction of the so called l-basis of strictly localized states and the Walsh-Husimi function of a state. In this context it is natural to study the so called Wehrl entropy of the state [20] (or the Wehrl entropy of the Walsh-Husimi function of the state to be more exact). They prove that the Wehrl entropy coincides with the Shannon entropy for their eigenstates. Our states are elements in the state space $L^2(\mathbb{Z}_N)$ and in our quantization $g \mapsto < Op(g)\psi, \psi >$ (see [12] for the definition of Op) is a signed measure, but does not induce a density on the phase space. Hence one might say that it is not natural to talk about Wehrl entropy in our quantization and we shall see what happens if one insists anyway: Let us pick ψ to be the function in (8), then for all $g \in C^\infty(\mathbb{T}^2)$ we have that

$$< Op(g)\psi, \psi >= \int_{\mathbb{T}^2} w(x)g(x)dx,$$

where $w(x)$ is the $p^{-k/2}-$periodic extension of

$$w(x) = \frac{1}{2p^k}\left(\delta_{0,0} + \delta_{p^{-k/2}/2,0} + \delta_{0,p^{-k/2}/2} - \delta_{p^{-k/2}/2,p^{-k/2}/2}\right).$$

This can be seen using Poisson's summation formula or by straightforward identification of Fourier coefficients. The distribution $w(x)$ is generally called the Wigner function and as the name indicates, people often want to think of this as a positive function, but obviously it is not. One naive way to cope with this problem would be to study trigonometric polynomials as observables and let the number of terms in the trigonometric expansion to grow with N. This solves our problems and makes it possible for us to approximate our sum of delta functions by a trigonometric polynomial. To be more precise: Let $\Omega \subset \mathbb{Z}^2$ be a bounded set and let $T(\Omega) = \{f(x) = \sum_{n\in\Omega} c_n e(n\cdot x); c_n \in \mathbb{C}\}$. Then for ψ given by (8) we have

$$< Op(g)\psi, \psi >= \int_{\mathbb{T}^2} \tilde{w}(x)g(x)dx,$$

for $g \in T(\Omega)$ and with $\tilde{w}(x) = \sum_{n\in\Omega\cap p^{k/2}\mathbb{Z}^2}(-1)^{n_1n_2}e(n\cdot x)$. The trigonometric polynomial $\tilde{w}(x)$ is often called the polynomial Wigner function and was introduced in [5] and has been studied also in [3]. In both these papers Ω is a rectangle with sides proportional to the inverse of Planck's constant and with one of the corners at the origin. When Ω is a rectangle we can simplify our expression for $\tilde{w}(x)$, using geometric sums repeatedly, to give an even more explicit formula. A problem is that if we allow Ω to be too large (area larger than N) it is easy to construct measures breaking the uncertainty relation and having negative entropy. For instance can the function $\tilde{\psi}(x) = \sum_{n\in\mathbb{Z}^2}\psi(x+n)$, where

$$\psi(x) = C\exp\{-N^{1+\epsilon}((x_1-1/2)^2 + (x_2-1/2)^2)\}$$

(this function is too localized at the position $(1/2, 1/2)$, breaking the Heisenberg uncertainty relation and having negative Wehrl entropy) be very well approximated by a positive trigonometric polynomial $\tilde{w_1}(x) = \sum_{n\in\Omega} c_n e(n\cdot x)$ if Ω is a disc of radius $N^{1/2+\epsilon'}$ and $\epsilon' > \epsilon/2$. With this in mind it seems natural to let Ω be a disc of radius square root of the inverse of Planck's constant, i.e.

$\Omega = \{x \in \mathbb{Z}^2; |x| < p^{k/2}\}$. This gives us $\tilde{w}(x) = 1$. Note that the Wehrl entropy of $\tilde{w}(x) = 1$ is maximal ($\log p^k$), but that the Shannon entropy of ψ is minimal. Heuristically we can understand why we have this disparity; on a large scale our state looks very uniform and have large entropy, but on a more local scale it looks very singular and have a small entropy. I hope this shows how careful one must be if one wants to use entropy of eigenstates to understand the ergodicity of the system.

5 Evaluation of Hecke eigenfunctions

The rest of the paper is devoted to the study of Hecke eigenfunctions in the orthogonal complement of $S_k(k-1,1)$. These are the functions which I called newforms in the introduction. In view of Theorem 3.3 we see that the newforms are the natural objects to study; a general Hecke eigenfunction can be thought of as a sum where each term is the image of T_m^{-1} of some newform (observe that T_0^{-1} is the identity operator). To get an easy description of the dynamics we will make the assumption that $N = p^{2k}$ where p is a prime larger than 3. The fact that the dynamics seems to be easier to describe if N is assumed to be a perfect square, has been observed before by Knabe [10]. Although his quantization is different, the description of the dynamics is quite similar. He also studies a preferred basis and this basis has a property close to our Lemma 5.1. This way of studying the dynamics also resembles somewhat to the introduction of "wave functions of Lagrangian subsets" introduced by Degli Esposti [4] and studied also in [5]. Since these articles are specialized to the case when N is a prime, the connection to my ζ_x-basis will be more apparent in my forthcoming paper for N being an odd exponent of p.

We begin the study by some basic definitions. The letters N, p, k will from now on always be related by $N = p^{2k}$.

Definition 5.1. For $x \in \mathbb{Z}_N$, let $\delta_x : \mathbb{Z}_N \to \mathbb{C}$ be the function which is 1 at x and 0 at every other point.

Definition 5.2. Given $x = \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} \in \mathbb{Z}_N^2$, let $\zeta_x : \mathbb{Z}_N \to \mathbb{C}$ be defined by

$$\zeta_x = \sum_{t \in \mathbb{Z}_{p^k}} e\left(\frac{x_1 t}{p^k}\right) \delta_{x_2 + p^k t}.$$

Remark. Notice that $\{\zeta_x; x \in \{1, 2, ..., p^k\}^2\}$ is an orthogonal basis of $L^2(\mathbb{Z}_N)$ and that $x \equiv x' \pmod{p^k}$ implies $\zeta_x = c\zeta_{x'}$ for some number c such that $c^{p^k} = 1$. In particular the space $\mathbb{C}\zeta_x$ can be thought of as defined for $x \in \mathbb{Z}_{p^k}^2$.

Definition 5.3. Given $D \in \mathbb{Z}_N$ we let

$$H_D = \left\{ \begin{pmatrix} a & bD \\ b & a \end{pmatrix}; a, b \in \mathbb{Z}_N \ , \ a^2 - Db^2 = 1 \right\}.$$

We make the assumption that A is not upper triangular modulo p. Because of this assumption A (or rather the image of A in $SL(2, \mathbb{Z}_N)$ can be written as $A = n_b h n_{-b}$ for some b, D and some $h \in H_D$ and so we see that the Hecke operators are given by $\{U_N(g); g \in n_b H_D n_{-b}\}$. But if ψ is an eigenfunction of $U_N(h)$, then $\widetilde{\psi} = U_N(n_b)\psi$ is an eigenfunction of $U_N(n_b h n_{-b})$ and furthermore $|\psi(x)| = |\widetilde{\psi}(x)|$. Thus we may assume that the Hecke operators are $\{U_N(h); h \in H_D\}$. If D is a quadratic residue modulo p then p is called split, if D is not a quadratic residue modulo p then p is called inert, and if $p|D$ then p is called ramified.

Definition 5.4. Let $\mathscr{N} : \mathbb{Z}_{p^k}^2 \to \mathbb{Z}_{p^k}$ be defined by $\mathscr{N}(x) = x_1^2 - Dx_2^2$.

Lemma 5.1. *Assume $B \in SL(2, \mathbb{Z}_N)$ and that $x' = Bx$. We have that*

$$U_N(B)\,\zeta_x = e\left(\frac{r(x_1'x_2' - x_1x_2)}{N}\right)\zeta_{x'}.$$

Proof. By the multiplicativity of both sides of the equality it is enough to prove the lemma for the generators of $SL(2, \mathbb{Z}_N)$. Since $N = p^{2k}$ we have that $\Lambda(t) = S_r\left(-1, p^{2k}\right) = 1$ and $2r \equiv 1 \pmod N$ (see [12]). Using the definition of U_N we get

$$\begin{aligned}
U_N(n_b)\,\zeta_x &= \sum_{t\in\mathbb{Z}_{p^k}} e\left(\frac{x_1t}{p^k}\right) e\left(\frac{rb\left(x_2 + p^kt\right)^2}{N}\right)\delta_{x_2+p^kt} \\
&= e\left(\frac{rbx_2^2}{N}\right)\sum_{t\in\mathbb{Z}_{p^k}} e\left(\frac{(x_1+bx_2)t}{p^k}\right)\delta_{x_2+p^kt} = e\left(\frac{r(x_1'x_2' - x_1x_2)}{N}\right)\zeta_{x'}, \\
U_N(a_s)\,\zeta_x &= \sum_{t\in\mathbb{Z}_{p^k}} e\left(\frac{x_1t}{p^k}\right)\delta_{s^{-1}(x_2+p^kt)} = \sum_{t\in\mathbb{Z}_{p^k}} e\left(\frac{sx_1t}{p^k}\right)\delta_{s^{-1}x_2+p^kt} \\
&= e\left(\frac{r(x_1'x_2' - x_1x_2)}{N}\right)\zeta_{x'}
\end{aligned}$$

and

$$\begin{aligned}
U_N(\omega)\,\zeta_x &= \sum_{t\in\mathbb{Z}_{p^k}} e\left(\frac{x_1t}{p^k}\right)\frac{1}{p^k}\sum_{z\in\mathbb{Z}_N}\delta_{x_2+p^kt}(z)e\left(\frac{2ryz}{N}\right) \\
&= \frac{e\left(\frac{x_2y}{N}\right)}{p^k}\sum_{t\in\mathbb{Z}_{p^k}} e\left(\frac{(x_1+y)t}{p^k}\right) = e\left(\frac{x_2y}{N}\right)\sum_{t\in\mathbb{Z}_{p^k}}\delta_{-x_1+p^kt} \\
&= \sum_{t\in\mathbb{Z}_{p^k}} e\left(\frac{x_2(-x_1+p^kt)}{N}\right)\delta_{-x_1+p^kt} = e\left(\frac{r(x_1'x_2' - x_1x_2)}{N}\right)\zeta_{x'}.
\end{aligned}$$

$\square$

As a special case of Lemma 5.1 we get the following corollary:

Corollary 5.2. *We have that*

$$U_N\begin{pmatrix} 1 & tp^kD \\ tp^k & 1 \end{pmatrix}\zeta_x = e\left(-\frac{r\mathscr{N}(x)t}{p^k}\right)\zeta_x.$$

Proof. With $x' = Bx$ we have

$$U_N \begin{pmatrix} 1 & tp^k D \\ tp^k & 1 \end{pmatrix} \zeta_x = e\left(\frac{r(x_1'x_2' - x_1x_2)}{N}\right)\zeta_{x'}$$
$$= e\left(\frac{r\left(x_1^2 + Dx_2^2\right)t}{p^k}\right) \sum_{s\in\mathbb{Z}_{p^k}} e\left(\frac{\left(x_1 + tp^k Dx_2\right)s}{p^k}\right)\delta_{x_2+tp^kx_1+sp^k}$$
$$= e\left(\frac{r\left(x_1^2 + Dx_2^2\right)t}{p^k}\right) \sum_{s\in\mathbb{Z}_{p^k}} e\left(\frac{x_1\left(s - tx_1\right)}{p^k}\right)\delta_{x_2+sp^k} = e\left(-\frac{r\mathscr{N}(x)t}{p^k}\right)\zeta_x.$$

□

Definition 5.5. For $C \in \mathbb{Z}_{p^k}$ we define

$$V_C = \bigoplus_{\substack{x\in\mathbb{Z}_{p^k}^2 \\ \mathscr{N}(x)=-C}} \mathbb{C}\zeta_x.$$

Since H_D preserves $\mathscr{N}(x)$ we see that V_C is invariant under the action of H_D. Moreover, if ψ is a Hecke eigenfunction, then Corollary 5.2 tells us that $\psi \in V_C$ for some $C \in \mathbb{Z}_{p^k}$. The main reason to study V_C is however the following property, which hold when $p \nmid C$: If a Hecke eigenfunction has a nonzero coefficient for some $\zeta_x \in V_C$, then it has nonzero coefficients for all $\zeta_x \in V_C$ and they have the same absolute value. To see this, pick some $x_0 \in \mathbb{Z}_{p^k}^2$ with $\mathscr{N}(x_0) = -C$. Since $H_D x_0 = \{x \in \mathbb{Z}_{p^k}^2; \mathscr{N}(x) = -C\}$ the claim follows from Lemma 5.1. We will use this property as one of the key ideas in evaluating Hecke eigenfunctions. If $p|C$ the orbit $H_D x_0$ is not always as large as $\{x \in \mathbb{Z}_{p^k}^2; \mathscr{N}(x) = -C\}$. This corresponds to the fact that the irreducible representations in V_C are no longer uniquely defined.

Note that $S_{2k}(2k-m,m) = \bigoplus_{p^m|x}\mathbb{C}\zeta_x \subseteq \bigoplus_{p^{2m}|C} V_C$ and that the bijections in Theorem 3.3 corresponds to dividing by p^m in the indexes of the ζ_x-functions. In particular the oldforms are linear combinations of ζ_x where $p|x$ and newforms are linear combinations of ζ_x where $p \nmid x$. If p is inert then $\mathscr{N}(x) \equiv 0 \pmod p$ implies $p|x$, thus $S_{2k}(2k-1,1) = \bigoplus_{p|C} V_C$. If p is split or ramified the implication is not true and there are newforms ψ such that $\psi \in V_C$ even when $p|C$.

Lemma 5.3. *If p does not divide C or D then* $\dim(V_C) = p^k - \left(\frac{D}{p}\right)p^{k-1}$.

Proof. To calculate the dimension we first prove that we can find x_1 and x_2 such that $x_1^2 \equiv -C + Dx_2^2 \pmod{p^k}$. This is done by induction on k where each induction step use Newton-Raphson approximation, a method known in number theory as Hensel's lemma. For $k = 1$ we have $(p+1)/2$ different squares, so both the left hand side and the right hand side assumes $(p+1)/2$ different values and by the pigeon hole principle we must have a solution to the equation. Now assume we have x_1 and x_2 such that $x_1^2 \equiv -C + Dx_2^2 \pmod{p^{n-1}}$. At least one of x_1 and x_2 is not divisible by p and we may assume that this is x_1. Putting $\widetilde{x_1} = x_1 - \left(x_1^2 - Dx_2^2 + C\right)/(2x_1)$ we see that $\widetilde{x_1}^2 \equiv -C + Dx_2^2 \pmod{p^n}$. Let $B = \begin{pmatrix} x_1 & x_2 D \\ x_2 & x_1 \end{pmatrix}$ have determinant congruent to $-C$ modulo p^k. We see that $V_C = U_N(B)V_1$, thus every V_C has the same dimension. We now count the number of $(x,y) \in \mathbb{Z}_{p^k}^2$ such that $x^2 - Dy^2 \equiv 0 \pmod{p}$: If $\left(\frac{D}{p}\right) = -1$ we immediately get $x \equiv y \equiv 0 \pmod{p}$ which gives p^{2k-2} solutions. But if $\left(\frac{D}{p}\right) = 1$ we also get the solutions $y \in \mathbb{Z}_{p^k}^\times$ and $x \equiv \pm\sqrt{D}y \pmod{p}$, so in this case the total number of solutions is $p^{2k-2} + 2p^{k-1}p^{k-1}(p-1) = (2p-1)p^{2k-2}$. From this we see that for $\left(\frac{D}{p}\right) = -1$ we have

$$\dim(V_C) = \frac{1}{p^{k-1}(p-1)} \dim\left(\bigoplus_{C \in \mathbb{Z}_{p^k}^\times} V_C\right) = \frac{p^{2k} - p^{2k-2}}{p^{k-1}(p-1)} = p^k + p^{k-1}$$

and for $\left(\frac{D}{p}\right) = 1$ we have

$$\dim(V_C) = \frac{1}{p^{k-1}(p-1)} \dim\left(\bigoplus_{C \in \mathbb{Z}_{p^k}^\times} V_C\right) = \frac{p^{2k} - (2p-1)p^{2k-2}}{p^{k-1}(p-1)} = p^k - p^{k-1}.$$

$\square$

The evaluation of a Hecke eigenfunction will lead to the study of the solutions to the equation $x^2 \equiv a \pmod{p^k}$. It is easy to see that if $a \not\equiv 0 \pmod{p^k}$ and p divides a an odd number of times, then the equation has no solutions. If however p divides a an even number of times we may reduce the equation to $\tilde{x}^2 \equiv \tilde{a} \pmod{p^{k-2s}}$, where $p \nmid \tilde{a}$. If $\tilde{a}$ is a square modulo p then this equation has two solutions $\pm x_0$ and the solutions to the original equation are $x \equiv \pm x_0 x^s + p^{k-s}m \pmod{p^k}$ for $m \in \mathbb{Z}_{p^s}$. If $a \equiv 0 \pmod{p^k}$ then the solutions are $x \equiv p^{\lceil k/2 \rceil}m \pmod{p^k}$ for $m \in \mathbb{Z}_{p^{[k/2]}}$. Since the solutions to the equation are written in quite different forms we formulate the evaluation in two different theorems corresponding to different right hand sides of the equation.

Theorem 5.4. *Let $\psi \in V_C$ be a normalized Hecke eigenfunction and assume that p does not divide C or D. Let $b \in \mathbb{Z}_N$ and assume that the equation $x^2 \equiv -C + Db^2 \pmod{p^k}$ has the solutions $x \equiv \pm x_0 p^s + p^{k-s}\mathbb{Z}_{p^s} \pmod{p^k}$ for some x_0 and s such that $p \nmid x_0$ and $0 \leqslant s < k/2$. Then*

$$\psi(b) = \frac{1}{\sqrt{1 - \left(\frac{D}{p}\right)\frac{1}{p}}} \left(\alpha_\psi(b) \sum_{z=1}^{p^s} e\left(\frac{q_+(z)}{p^s}\right) + \beta_\psi(b) \sum_{z=1}^{p^s} e\left(\frac{q_-(z)}{p^s}\right) \right), \tag{10}$$

where $q_\pm(z) = r\left(\Theta_\psi(b)z \pm x_0 Dbz^2 + p^{k-2s}3^{-1}D^2b^2z^3\right)$ and $|\alpha_\psi(b)| = |\beta_\psi(b)| = 1$.

Remark. The function $\Theta_\psi(b)$, which takes values in $\mathbb{Z}_{p^s}$, will be specified in equation (11).

Proof. We know that ψ is a linear combination of ζ_x such that $\mathscr{N}(x) = -C$. Fixing x_0, any such x can be written as hx_0 for some $h \in H_D$, hence it follows from Lemma 5.1 that all constants in this linear combination have the same absolute value R. The orthogonality of $\{\zeta_x; x \in \{1,2,...,p^k\}^2\}$ and Lemma 5.3 gives

$$1 = \|\psi\|_2^2 = \left(p^k - \left(\frac{D}{p}\right) p^{k-1}\right) \frac{R^2}{p^k},$$

thus $R = \left(1 - \left(\frac{D}{p}\right) \frac{1}{p}\right)^{-1/2}$. Since $\zeta_x(b) = 0$ unless $x_2 \equiv b \pmod{p^k}$ the value of $\psi(b)$ is only a sum over $x \in \mathbb{Z}_{p^k}^2$ such that $x_1^2 \equiv -C + Db^2 \pmod{p^k}$ and $x_2 \equiv b \pmod{p^k}$. By the assumptions of the theorem we have that $x_1 \equiv \pm x_0 p^s + p^{k-s}\mathbb{Z}_{p^s} \pmod{p^k}$ and we see that the values of x can be represented by the elements

$$\left\{ B(s)^z \begin{pmatrix} x_0 p^s \\ b \end{pmatrix}; z = 0,1,...,p^s - 1 \right\} \cup \left\{ B(s)^z \begin{pmatrix} -x_0 p^s \\ b \end{pmatrix}; z = 0,1,...,p^s - 1 \right\}$$

in $\mathbb{Z}_N^2$. Here $B(s) = \begin{pmatrix} 1 + rDp^{2(k-s)} & p^{k-s}D \\ p^{k-s} & 1 + rDp^{2(k-s)} \end{pmatrix}$ and by induction it is easy to show that

$$B(s)^z = \begin{pmatrix} 1 + rDz^2p^{2(k-s)} & \left(p^{k-s}z + 3^{-1}rDp^{3(k-s)}(z^3 - z)\right) D \\ p^{k-s}z + 3^{-1}rDp^{3(k-s)}(z^3 - z) & 1 + rDz^2p^{2(k-s)} \end{pmatrix}.$$

Denote $\zeta_{\pm,z} = \zeta_{B(s)^z \binom{\pm x_0 p^s}{b}}$ and call the constants in front of these functions $Ra_{\pm,z}$. We have that

$$\psi(b) = R \left(\sum_{z=0}^{p^s-1} a_{+,z}\zeta_{+,z}(b) + \sum_{z=0}^{p^s-1} a_{-,z}\zeta_{-,z}(b) \right).$$

If we use Lemma 5.1 we see that $U_N(B(s))\zeta_{\pm,z-1} = e\left(\frac{r(f_\pm(z) - f_\pm(z-1))}{N}\right)\zeta_{\pm,z}$ for $z = 1,...,p^s - 1$, where

$$\begin{aligned} f_\pm(z) &= \left(\pm\left(1 + rDz^2p^{2(k-s)}\right)p^s x_0 + \left(p^{k-s}z + 3^{-1}rDp^{3(k-s)}(z^3 - z)\right)Db\right) \\ &\quad \times \left(\pm\left(p^{k-s}z + 3^{-1}rDp^{3(k-s)}(z^3 - z)\right)p^s x_0 + \left(1 + rDz^2p^{2(k-s)}\right)b\right) \\ &\equiv \pm p^s x_0 b + p^{k-s}\left(Db^2 + p^{2s}x_0^2 - p^{2(k-s)}3^{-1}rD^2b^2\right)z \\ &\quad \pm p^{2k-s}2x_0Dbz^2 + p^{3(k-s)}3^{-1}2D^2b^2z^3 \pmod{N}. \end{aligned}$$

Since $B(s)^{p^s} = \begin{pmatrix} 1 & p^kD \\ p^k & 1 \end{pmatrix}$ Corollary 5.2 gives us that $U_N(B(s))\psi = e\left(\frac{r\widetilde{C}}{p^{k+s}}\right)\psi$ for some $\widetilde{C} \equiv C \pmod{p^k}$ and this leads to

$$\begin{aligned} a_{\pm,z} &= e\left(\frac{-r\widetilde{C}}{p^{k+s}}\right) e\left(\frac{r\left(f_\pm(z) - f_\pm(z-1)\right)}{N}\right) a_{\pm,z-1} \\ &= e\left(\frac{-r\widetilde{C}z}{p^{k+s}}\right) e\left(\frac{r\left(f_\pm(z) - f_\pm(0)\right)}{N}\right) a_{\pm,0}. \end{aligned}$$

But $\zeta_{\pm,z}(b) = e\left(\frac{-p^{k+s}x_0^2 z \mp p^{2k-s}3rx_0Dbz^2 - p^{3(k-s)}rD^2b^2z^3}{N}\right)$ hence

$$a_{\pm,z}\zeta_{+,z}(b) = e\left(\frac{-p^{k-s}r\widetilde{C}z + rf_{\pm}(z) - rf_{\pm}(0) - p^{k+s}x_0^2 z}{N}\right)$$
$$\times\, e\left(\frac{\mp p^{2k-s}3rx_0Dbz^2 - p^{3(k-s)}rD^2b^2z^3}{N}\right) a_{\pm,0} = a_{\pm,0}e\left(\frac{q_{\pm}(z)}{p^s}\right),$$

where $q_{\pm}(z) = r\left(\Theta_{\psi}(b)z \pm x_0Dbz^2 + p^{k-2s}3^{-1}D^2b^2z^3\right)$ and

$$\Theta_{\psi}(b)p^k \equiv -x_0^2p^{2s} - \widetilde{C} + Db^2 - p^{2(k-s)}3^{-1}rD^2b^2 \pmod{p^{k+s}}. \qquad (11)$$

Remark. Note that $\Theta_{\psi}(b)$ is well defined, but that it can not be lifted to an integer polynomial. Different Hecke eigenfunctions in V_C correspond to different choices of $\widetilde{C} \equiv C \pmod{p^k}$.

□

Theorem 5.5. *Let $\psi \in V_C$ be a normalized Hecke eigenfunction for some $C \in \mathbb{Z}_{p^k}^{\times}$. If $b \in \mathbb{Z}_N$ fulfills that $-C + Db^2 \equiv 0 \pmod{p^k}$ then*

$$\psi(b) = \frac{\alpha_{\psi}(b)}{\sqrt{1 - \left(\frac{D}{p}\right)\frac{1}{p}}}\sum_{z=1}^{p^{[k/2]}} e\left(\frac{q(z)}{p^{[k/2]}}\right), \qquad (12)$$

where $q(z) = r\left(\Theta_{\psi}(b)z + p^{k-2[k/2]}3^{-1}CDz^3\right)$, $|\alpha_{\psi}(b)| = 1$ and

$$\Theta_{\psi}(b)p^k \equiv -\widetilde{C} + Db^2 - p^{k+(k-2[k/2])}3^{-1}rCD \pmod{p^{[3k/2]}}.$$

Proof. This is the same proof as for Theorem 5.4. □

6 Exponential sums of cubic polynomials

We have seen that the values of the Hecke eigenfunctions are given by exponential sums over rings $\mathbb{Z}_{p^s}$. In this chapter we will derive the results we need in order to study the supremum of the eigenfunctions. The methods we use are both elementary and well known and more general results may be found in chapter 12 of [8]. For convenience we will still assume that $p > 3$.

Definition 6.1. Let n be a nonnegative integer. For $q \in \mathbb{Z}_{p^n}[x]$ we define

$$S(q,n) = \sum_{z=1}^{p^n} e\left(\frac{q(z)}{p^n}\right).$$

Lemma 6.1. *Let $q(z) = a_3z^3 + a_2z^2 + a_1z + a_0$ and assume that $p|a_3$ but $p \nmid a_2$. Then $|S(q,n)| = p^{n/2}$.*

Proof. It is trivial to see that $|S(q,0)| = 1 = p^{0/2}$. On the other hand $S(q,1) = \sum_{z=1}^{p} e\left(\frac{a_2z^2+a_1z+a_0}{p}\right)$ and this Gauss sum is well known to have absolute value equal to $p^{1/2}$ (cf. [18] chapter II.3). Now assume $n > 1$. The observation that we will use and use repeatedly is that if we have a polynomial $q \in \mathbb{Z}_{p^n}[z]$ then $q(z_1 + p^{n-1}z_2) \equiv q(z_1) + q'(z_1)p^{n-1}z_2 \pmod{p^n}$. In this case this gives us that

$$\begin{aligned}
S(q,n) &= \sum_{z=1}^{p^n} e\left(\frac{q(z)}{p^n}\right) = \sum_{z_1=1}^{p^{n-1}} \sum_{z_2=1}^{p} e\left(\frac{q(z_1+p^{n-1}z_2)}{p^n}\right) \\
&= \sum_{z_1=1}^{p^{n-1}} \sum_{z_2=1}^{p} e\left(\frac{q(z_1)+q'(z_1)p^{n-1}z_2}{p^n}\right) \\
&= p \sum_{\substack{z_1 \in \mathbb{Z}_{p^{n-1}} \\ q'(z_1) \equiv 0 \pmod{p}}} e\left(\frac{q(z_1)}{p^n}\right) = p \sum_{\substack{z_1 \in \mathbb{Z}_{p^{n-1}} \\ z_1 \equiv -a_1 r a_2^{-1} \pmod{p}}} e\left(\frac{q(z_1)}{p^n}\right) \\
&= p \sum_{z=1}^{p^{n-2}} e\left(\frac{q(-a_1ra_2^{-1}+zp)}{p^n}\right) = p\; e\left(\frac{q(-a_1ra_2^{-1})}{p^n}\right) S(q_1, n-2),
\end{aligned}$$

where q_1 is a polynomial of degree 3 which fulfills the assumptions of the lemma. The proof now follows by induction. □

Lemma 6.2. *Let $q(z) = a_3z^3 + a_1z + a_0$ and assume that $p \nmid a_3$ and that $p^2 \nmid a_1$. Then $|S(q,n)| \leqslant 2p^{n/2}$.*

Proof. For $n = 1$ this is well known, see for instance [18], therefore we assume that $n > 1$. Using the same calculation as in the proof of Lemma 6.1 we obtain that

$$S(q,n) = p \sum_{\substack{z_1 \in \mathbb{Z}_{p^{n-1}} \\ q'(z_1) \equiv 0 \pmod{p}}} e\left(\frac{q(z_1)}{p^n}\right). \tag{13}$$

The equation $q'(z_1) \equiv 0 \pmod{p}$ has at most two solutions modulo p, hence this expression consists of at most two different sums of length p^{n-2}. If $p \nmid a_1$ these sums are of the form $e\left(x_0p^{-n}\right) S(q_1, n-2)$, where $x_0 \in \mathbb{Z}$ and q_1 fulfills the assumptions of Lemma 6.1. On the other hand, if $a_1 = \tilde{a_1}p$ with $p \nmid \tilde{a_1}$, we get

$$\begin{aligned}
S(q,n) &= p \sum_{\substack{z_1 \in \mathbb{Z}_{p^{n-1}} \\ q'(z_1) \equiv 0 \pmod{p}}} e\left(\frac{q(z_1)}{p^n}\right) = p\; e\left(\frac{a_0}{p^n}\right) \sum_{z_1=1}^{p^{n-2}} e\left(\frac{a_3pz_1^3 + \tilde{a_1}z_1}{p^{n-2}}\right) \\
&= p^2\; e\left(\frac{a_0}{p^n}\right) \sum_{\substack{z_1 \in \mathbb{Z}_{p^{n-3}} \\ \tilde{a_1} \equiv 0 \pmod{p}}} e\left(\frac{a_3pz_1^3 + \tilde{a_1}z_1}{p^{n-2}}\right) = 0.
\end{aligned}$$

□

Lemma 6.3. *Let $q(z) = a_3z^3 + p^2a_1z + a_0$ and assume that $p \nmid a_3$. For $n \geqslant 3$ we have that $|S(q,n)| = p^2|S(q_1, n-3)|$, where $q_1(z) = a_3z^3 + a_1z$.*

Proof. Again we write

$$S(q,n) = p \sum_{\substack{z_1 \in \mathbb{Z}_{p^{n-1}} \\ q'(z_1) \equiv 0 \pmod p}} e\left(\frac{q(z_1)}{p^n}\right) = p\ e\left(\frac{a_0}{p^n}\right) \sum_{z_1=1}^{p^{n-2}} e\left(\frac{q_1(z_1)}{p^{n-3}}\right)$$
$$= p^2\ e\left(\frac{a_0}{p^n}\right) S(q_1, n-3).$$

□

Definition 6.2. For $\alpha \in \mathbb{Z}_{p^n}^{\times}$ and $n = 1$ or $n = 2$ we define

$$A_{\alpha,n} = \frac{\sup_{t \in \mathbb{Z}_{p^n}} |S(q_{\alpha,t}, n)|}{p^{n/2}},$$

where $q_{\alpha,t}(z) = \alpha z^3 + tz$.

Remark. $A_{\alpha,n}$ is of course a function of p but this is suppressed since we often think of p as fixed.

Lemma 6.4. *For fixed n and p, $A_{\alpha,n}$ assumes at most three different values and if $p \equiv 2 \pmod 3$ then $A_{\alpha,n}$ is independent of α. Moreover, $1 \leqslant A_{\alpha,1} \leqslant 2$ and $\sqrt{2} < A_{\alpha,2} \leqslant 2$.*

Proof. Since the multiplicative group $\mathbb{Z}_{p^n}^{\times}$ is cyclic of order $(p-1)p^{n-1}$ we write the elements as g^k, where $k \in \mathbb{Z}_{(p-1)p^{n-1}}$. If $p \equiv 2$ (mod 3) then 3 is invertible in $\mathbb{Z}_{(p-1)p^{n-1}}$ so we see that $g^k = (g^{k/3})^3$ is a cube. If $p \equiv 1$ (mod 3) any element can be written as $g^l\left(g^k\right)^3$ where $l = 0, 1, 2$. We have that

$$A_{\alpha\beta^3,n} = \frac{\sup_{t \in \mathbb{Z}_{p^n}} |S(q_{\alpha\beta^3,t}, n)|}{p^{n/2}} = \frac{\sup_{t \in \mathbb{Z}_{p^n}} |S(q_{\alpha,t\beta^{-1}}(\beta z), n)|}{p^{n/2}} = A_{\alpha,n}$$

and from this the first claim follows. To prove that $A_{\alpha,1} \geqslant 1$ we notice that $\left\{e\left(\frac{-tz}{p}\right)\right\}_{t \in \mathbb{Z}_p}$ is an orthonormal basis in $L^2\left(\mathbb{Z}_p\right)$. Thus

$$1 = \left\| e\left(\frac{\alpha z^3}{p}\right)\right\|_2^2 = \sum_{t \in \mathbb{Z}_p} \left|\left\langle e\left(\frac{\alpha z^3}{p}\right), e\left(\frac{-tz}{p}\right)\right\rangle\right|^2$$
$$\leqslant p \sup_{t \in \mathbb{Z}_p} \left|\frac{1}{p} S(q_{\alpha,t}, 1)\right|^2 = A_{\alpha,1}^2.$$

To prove that $A_{\alpha,2} > \sqrt{2}$ we use the same proof but we notice that we only have to sum over t such that $S(q_{\alpha,t}, 2) \neq 0$. By the proof of Lemma 6.2 we see that this gives us that $t \equiv 0 \pmod p$ or that t is a unit such that $-3^{-1}\alpha^{-1}t$ is a square (otherwise the sum in (13) is empty). The number of such t is less than $p^2/2$ and that gives our estimate. That $A_{\alpha,n} \leqslant 2$ follows directly from Lemma 6.2 and the fact that $|S(\alpha z^3, 2)| = p$. □

Theorem 6.5. *If $q_{\alpha,t}(z) = \alpha z^3 + tz$ and $\alpha \in \mathbb{Z}_{p^n}^{\times}$ then*

$$\sup_{t \in \mathbb{Z}_{p^n}} |S(q_{\alpha,t}, n)| = \begin{cases} p^{2n/3} & \textit{if } n \equiv 0 \pmod 3 \\ A_{\alpha,1} p^{2n/3 - 1/6} & \textit{if } n \equiv 1 \pmod 3 \\ A_{\alpha,2} p^{2n/3 - 1/3} & \textit{if } n \equiv 2 \pmod 3 \end{cases}.$$

Proof. For $n = 0, 1, 2$ the proof is trivial, hence assume $n \geqslant 3$. We see that $\sup_{t\in\mathbb{Z}_{p^n}} |S(q_{\alpha,t}, n)| = \max\left(\sup_{p^2|t} |S(q_{\alpha,t}, n)|, \sup_{p^2\nmid t} |S(q_{\alpha,t}, n)|\right)$ and that the last of the two expressions is less than $2p^{n/2}$ by Lemma 6.2. The first expression is equal to $p^2 \sup_{t\in\mathbb{Z}_{p^{n-3}}} |S(q_{\alpha,t}, n-3)|$ by Lemma 6.3 and this is always larger than $2p^{n/2}$ since $\sqrt{p} > 2$. The theorem now follows by induction. □

7 Supremum norms of Hecke eigenfunctions in V_C

From [13] and [11] we know that normalized Hecke eigenfunctions fulfill

$$\|\psi\|_\infty \leqslant \frac{2}{\sqrt{1 - \left(\frac{D}{p}\right)\frac{1}{p}}}$$

if $N = p$ and as we will see this is also true for $N = p^2$ (if ψ is orthogonal to $S_2(1, 1)$) and for "half" of the Hecke eigenfunctions for a general $N = p^{2k}$. In fact, this estimate is a very good approximation of the supremum norm of these functions:

Theorem 7.1. *Let $N = p^{2k}$ for some prime $p > 3$ that does not divide C or D and assume that $\psi \in V_C$ is a normalized Hecke eigenfunction. If $\left(\frac{C}{p}\right) = -\left(\frac{D}{p}\right)$ or if $k = 1$ then*

$$\frac{2}{\sqrt{1 - \left(\frac{D}{p}\right)\frac{1}{p}}}\left(1 - \frac{\pi^2}{8N}\right) \leqslant \|\psi\|_\infty \leqslant \frac{2}{\sqrt{1 - \left(\frac{D}{p}\right)\frac{1}{p}}}.$$

Proof. We see that if $\left(\frac{C}{p}\right) = -\left(\frac{D}{p}\right)$ then $-C + Db^2 \not\equiv 0 \pmod{p}$ for all b, hence Theorem 5.4 immediately gives

$$\|\psi\|_\infty \leqslant \frac{2}{\sqrt{1 - \left(\frac{D}{p}\right)\frac{1}{p}}} \tag{14}$$

in this situation. If $k = 1$ then $s = 0$ in Theorem 5.4 and $[k/2] = 0$ in Theorem 5.5, and this also gives the estimation (14). To prove the other inequality we pick $b \in \mathbb{Z}_N$ such that $\left(\frac{-C+Db^2}{p}\right) = 1$. We know (using the notation from the proof of Theorem 5.4) that

$$\begin{aligned}
\psi\left(b + tp^k\right) &= \frac{1}{\sqrt{1 - \left(\frac{D}{p}\right)\frac{1}{p}}}\left(a_{+,0}\zeta_{+,0}\left(b + tp^k\right) + a_{-,0}\zeta_{-,0}\left(b + tp^k\right)\right) \\
&= \frac{1}{\sqrt{1 - \left(\frac{D}{p}\right)\frac{1}{p}}}\left(e\left(\frac{x_0 t}{p^k}\right) a_{+,0}\zeta_{+,0}(b) + e\left(\frac{-x_0 t}{p^k}\right) a_{-,0}\zeta_{-,0}(b)\right) \\
&= \frac{e\left(\frac{-x_0 t}{p^k}\right) a_{+,0}\zeta_{+,0}(b)}{\sqrt{1 - \left(\frac{D}{p}\right)\frac{1}{p}}}\left(e\left(\frac{2x_0 t}{p^k}\right) + \frac{a_{-,0}\zeta_{-,0}(b)}{a_{+,0}\zeta_{+,0}(b)}\right).
\end{aligned}$$

Since $x_0 \not\equiv 0 \pmod{p}$ we can pick t so that the difference θ of the arguments of the two expressions in the parenthesis is at most π/p^k. Remembering that both the $a_{\pm,0}$ and $\zeta_{+,0}(b)$ have absolute value 1 we see that this t gives us

$$\left|\psi\left(b+tp^k\right)\right| = \frac{\sqrt{2+2\cos\theta}}{\sqrt{1-\left(\frac{D}{p}\right)\frac{1}{p}}} \geqslant \frac{2-\frac{\theta^2}{4}}{\sqrt{1-\left(\frac{D}{p}\right)\frac{1}{p}}} \geqslant \frac{2}{\sqrt{1-\left(\frac{D}{p}\right)\frac{1}{p}}}\left(1-\frac{\pi^2}{8N}\right).$$

□

The other "half" (neglecting $\bigoplus_{p|C} V_C$ for a moment) of the Hecke eigenfunctions have rather large supremum norms. As we shall see shortly these supremum norms assume at most three different values for a fixed N.

Theorem 7.2. *Let $N = p^{2k}$ for some prime $p > 3$ and assume that $\psi \in V_C$ is a normalized Hecke eigenfunction for some $C \in \mathbb{Z}_{p^k}^\times$. If $\left(\frac{C}{p}\right) = \left(\frac{D}{p}\right)$ and $k > 1$ then*

$$\|\psi\|_\infty = \frac{1}{\sqrt{1-\left(\frac{D}{p}\right)\frac{1}{p}}} \times \begin{cases} p^{k/3} & \text{if } k \equiv 0 \pmod{3} \\ A_{36CD,2}\ p^{k/3-1/3} & \text{if } k \equiv 1 \pmod{3} \\ A_{36CD,1}\ p^{k/3-1/6} & \text{if } k \equiv 2 \pmod{3} \end{cases}. \tag{15}$$

Proof. Let us first estimate the expression in Theorem 5.4, that is equation (10): If $b \equiv 0 \pmod{p}$ then $x^2 \equiv -C + Db^2 \pmod{p^k}$ has at most 2 different solutions and therefore we may assume that b is a unit because otherwise $|\psi(b)|$ is much smaller than the expressions in equation (15). But then $|S(q_\pm, s)| = p^{s/2}$ by Lemma 6.1, hence

$$|\psi(b)| \leqslant \frac{2p^{s/2}}{\sqrt{1-\left(\frac{D}{p}\right)\frac{1}{p}}} \leqslant \frac{2p^{(k-1)/4}}{\sqrt{1-\left(\frac{D}{p}\right)\frac{1}{p}}}.$$

We see that this is less than the claimed supremum norm if $k > 2$. If however $k = 2$ then $s = 0$ and using this we see that $|\psi(b)|$ is small also in this case. The expression in Theorem 5.5 (equation (12)) has absolute value $\left|\psi\left(b+tp^k\right)\right| = \left(1-\left(\frac{D}{p}\right)\frac{1}{p}\right)^{-1/2}|S(q,[k/2])|$ where

$$q(z) = r\left(\Theta_\psi\left(b+tp^k\right)z + p^{k-2[k/2]}3^{-1}CDz^3\right).$$

By the definition of Θ_ψ we have that

$$\begin{aligned}\Theta_\psi\left(b+tp^k\right)p^k &\equiv -\widetilde{C} + D\left(b+tp^k\right)^2 - p^{k+(k-2[k/2])}3^{-1}rCD \\ &\equiv \left(\Theta_\psi(b) + 2Dbt\right)p^k \pmod{p^{[3k/2]}}.\end{aligned}$$

Since $p \nmid 2Db$ we see that, as we let t run through all elements in $\mathbb{Z}_{p^k}$, the polynomial q run through all polynomials of the form $q_\alpha(z) = \alpha z + p^{k-2[k/2]}3^{-1}rCDz^3$ with $\alpha \in \mathbb{Z}_{p^{[k/2]}}$. We now study the cases when k is even and when k is odd separately: If k is odd we get $S(q_\alpha,[k/2]) = 0$ if $p \nmid \alpha$, hence

$$\sup_{\alpha\in\mathbb{Z}_{p^{[k/2]}}} |S(q_\alpha,[k/2])| = p \sup_{\alpha\in\mathbb{Z}_{p^{[k/2]-1}}} |S(w_\alpha,[k/2]-1)|,$$

where $w_\alpha(z) = \alpha z + 3^{-1} rCDz^3$. Applying Theorem 6.5 we get the expression we want. (Lemma 6.4 says that $A_{3^{-1}rCD,n} = A_{36CD,n}$.) If k is even we have that $q_\alpha = w_\alpha$ and we can apply Theorem 6.5 directly to get the desired expression. $\square$

For completeness we also study the case when $p|D$, that is the ramified case. Our evaluation procedure for the Hecke operators still works and we get the following result which is somewhat analogous to the known result for primes, see [11].

Proposition 7.3. *Let $\psi \in V_C$ be a normalized Hecke eigenfunction for some $C \in \mathbb{Z}_{p^k}^\times$ and assume that $p|D$. We have that*

$$\sqrt{2}\left(1 - \frac{\pi^2}{8N}\right) \leqslant \|\psi\|_\infty \leqslant \sqrt{2}.$$

Proof. Let us determine the dimension of V_C, that is the number of solutions to $x_1^2 - Dx_2^2 = -C$ in $\mathbb{Z}_{p^k}$. This is easy because for any x_2 the equation $x_1^2 = -C + Dx_2^2$ has exactly two solutions so the total number of solutions is $2p^k$. We fix some x_0 such that $\mathscr{N}(x_0) = -C$ and we notice that every x with $\mathscr{N}(x) = -C$ can be written as hx_0 for some $h \in H_D$. This shows that ψ is a sum of ζ_x-functions where $\mathscr{N}(x) = -C$ and the constants in front of them have absolute value $\sqrt{p^k/(2p^k)} = 1/\sqrt{2}$. We now argue as in the proof of Theorem 7.1 to get the desired conclusion. $\square$

Last we will turn our focus to the case when $p|C$. This implies that p is either split or ramified. The case when $p|C$ and p is ramified will not be treated in this paper but one can expect that the supremum norms in that case behave in the same manner as in Theorem 7.2. Now assume that p is split and let $\sqrt{D}$ be an element in $\mathbb{Z}_N$ such that $\sqrt{D}^2 = D$. Now define

$$V_+ = \bigoplus_{\substack{x \in \mathbb{Z}_{p^k}^2 \\ x_1 \equiv \sqrt{D} x_2 \not\equiv 0 \pmod{p}}} \mathbb{C}\zeta_x.$$

and V_- in the same manner but with a minus sign in front of $\sqrt{D}$. Note that $\bigoplus_{p|C} V_C = V_+ \oplus V_- \oplus S_{2k}(2k-1, 1)$ and that $V_\pm$ are invariant under the action of H_D.

Proposition 7.4. *Let $N = p^{2k}$ for some prime $p > 3$ and assume that $p|C$ and that D is a quadratic residue modulo p. If $\psi \in V_C \cap V_\pm$ is a normalized Hecke eigenfunction then*

$$|\psi(b)| = \begin{cases} \frac{1}{\sqrt{1-\frac{1}{p}}} & \text{if } p \nmid b \\ 0 & \text{if } p|b \end{cases}.$$

Proof. We may assume that $\psi \in V_C \cap V_+$. To prove the theorem the main difficulty is to prove the following claim: If $\zeta_x, \zeta_y \in V_C \cap V_+$ there is an $h \in H_D$ such that $hx \equiv y \pmod{p^k}$. Assume that $p^l|C$ but $p^{l+1} \nmid C$. We see that $x_1 \equiv \sqrt{D}x_2 \pmod{p^l}$ and that the same equality holds for y. But then $p^l|x_1y_2 - x_2y_1$ and we see that we can choose h_2 so that $-Ch_2 \equiv x_1y_2 - x_2y_1 \pmod{p^k}$. This determines h_2 modulo p^{k-l}. Now choose $h_1 \equiv (y_1 - Dx_2h_2)x_1^{-1} \pmod{p^k}$ and put $h = \begin{pmatrix} h_1 & h_2 D \\ h_2 & h_1 \end{pmatrix}$. It is straightforward to verify that $hx \equiv y \pmod{p^k}$, but in general $h \notin H_D$. In fact calculations show that $h_1^2 - Dh_2^2 \equiv (y_1^2 - (x_1 y_2 + x_2 y_1) D h_2) x_1^{-2} \pmod{p^k}$ and we notice that the expression in front of h_2 is invertible. Since h_2 only is determined modulo p^{k-l} we can choose h_2 so that $h \in H_D$ as long as we can show that $\det(h) \equiv 1 \pmod{p^{k-l}}$. But this follows immediately from the fact that $-C \equiv \mathcal{N}(y) \equiv \mathcal{N}(hx) \equiv -C \det(h) \pmod{p^k}$.

Let $\psi \in V_C \cap V_+$. The dimension of $V_C \cap V_+$ is $p^{k-1}(p-1)$, hence ψ is a linear combination of ζ_x where the coefficients have absolute value $\sqrt{p^k/(p^{k-1}(p-1))} = (1-1/p)^{-1/2}$. We see that if $p \nmid b$ then $x^2 \equiv -C + Db^2 \pmod{p^k}$ has exactly one solution such that $x \equiv \sqrt{D}b \pmod{p}$ and if $p|b$ the equation has no solutions such that $x \not\equiv 0 \pmod{p}$. □

Remark. If $p|C$ and $\psi \in V_C$ is a normalized Hecke eigenfunction orthogonal to $S_{2k}(2k-1, 1)$, then Cauchy-Schwarz inequality applied to Proposition 7.4 gives us

$$\|\psi\|_\infty \leqslant \sqrt{\frac{2}{1-\frac{1}{p}}}.$$

Theorem 7.5. *Let $N = p^{2k}$ for some prime $p > 3$ and assume that $p \nmid D$. If $\psi \in L^2(\mathbb{Z}_N)$ is a normalized Hecke eigenfunction then $\|\psi\|_\infty \leqslant N^{1/4}$.*

Proof. First assume that p is inert. Then there is an integer $0 \leqslant m \leqslant k$ such that $\psi \in S_{2k}(2k-m, m)$ but $\psi \notin S_{2k}(2k-m-1, m+1)$. By Theorem 3.3 $\psi \in S_{2k}(2k-m, m) \cong L^2(\mathbb{Z}_{p^{2k-2m}})$ and it is obvious that $T_m\psi$ must belong to V_C for some $C \in \mathbb{Z}^\times_{p^{2k-2m}}$. Hence the estimates in Theorem 7.1 and Theorem 7.2 together with the fact that T_m is unitary gives the estimate directly. Now assume that p is split. If $\psi \in V_C$ for some $C \in \mathbb{Z}^\times_{p^{2k}}$ then Theorem 7.1 and Theorem 7.2 gives the estimate. If $\psi \in V_C$ and $p|C$ we write $\psi = \psi_0 + \psi_1 + ... + \psi_l$, for some $l \leqslant k$. ψ_m is constructed so that $\psi_m \in S_{2k}(2k-m, m)$ but ψ_m is orthogonal to $S_{2k}(2k-m-1, m+1)$. Theorem 7.4 together with Theorem 3.3 tells us that the support of ψ_m for $m < l$ is $\{x; p^m | x \wedge p^{m+1} \nmid x\}$, hence the supports are all disjoint and we see that $\|\psi\|_\infty = \max_{0 \leqslant m \leqslant k} \|\psi_m\|_\infty$. By our last remark we see that

$$\|\psi_m\|_\infty \leqslant \sqrt{\frac{2}{1-\frac{1}{p}}}\, p^{m/2} \|\psi_m\|_2 \leqslant \sqrt{\frac{2}{1-\frac{1}{p}}}\, p^{m/2}$$

for $m < l$ and $\|\psi_l\|_\infty \leqslant p^{k/2} \|\psi_k\|_2 \leqslant p^{k/2}$. □

Remark. Note that Theorem 7.5 is true for all N' that could be written as a product of different N of the form stipulated in the theorem. Also note that the estimates $|\psi(x)| \leqslant \|\psi\|_\infty \leqslant N^{1/4}$ implies that $h(\psi) \geqslant \frac{1}{2} \log N$, the estimate in Theorem 4.1.

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