Moduli spaces of irreducible symplectic manifolds

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Abstract

We study the moduli spaces of polarised irreducible symplectic mani-
folds. By a comparison with locally symmetric varieties of orthogonal
type of dimension 20, we show that the moduli space of polarised de-
formation $K^3[2]$ manifolds with polarisation of degree $2d$ and split type
is of general type if $d \geq 12$.

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0 Introduction

A simply-connected compact complex Kähler manifold is called an irre-
ducible symplectic manifold if it has an everywhere nondegenerate 2-form,
unique up to scalar. Irreducible symplectic manifolds are also known as ir-
reducible hyperkähler manifolds, and for brevity are frequently referred to
simply as symplectic manifolds, omitting the word “irreducible”. They have
been extensively studied by Beauville, Bogomolov, Debarre, Fujiki, Huy-
brechts, Markman, Namikawa and O'Grady among others. Irreducible sym-
plectic manifolds have even complex dimension: in the surface case they are
the K3 surfaces. However, relatively few examples are known. Background,
and considerable detail, may be found in Huybrechts’ lecture notes [Huy3].

The second cohomology $H^2(X, \mathbb{Z})$ of a symplectic manifold $X$ carries a
nondegenerate quadratic form $q_X$ of signature $(3, b_2(X) - 3)$, called the
Beauville form, or Beauville-Bogomolov form. Usually the lattice $L = (H^2(X, \mathbb{Z}), q_X)$ is not unimodular, nor is it known to be necessarily even,
although it is even in all known examples. A polarisation on $X$ is a choice
of ample line bundle on $X$, or equivalently the cohomology class $h$ of an
ample line bundle. The (Beauville) degree of the polarisation is defined to
be $d = q_X(h)$: it is positive. There is a period map for symplectic mani-

fields: the global Torelli theorem, however, is known to fail in some cases
(see [Deb], [Nam]).

Our aim in this paper is to study the moduli of polarised symplectic
manifolds by means of the period map. In Section 1 we describe this con-
struction precisely, prove that the moduli spaces exist and show how they are
related to locally symmetric varieties of orthogonal type: see Theorem 1.5.
These varieties are associated with the orthogonal complement $L_{h^\perp}$ of $h$ in $L$. What lattice $L_{h^\perp}$ is depends in general on the choice of $h$, not just on the degree as in the case of K3 surfaces. The results of Section 1 hold for all classes of irreducible symplectic manifolds.

In Section 2 we specialise to the case of deformation $K3[n]$ manifolds: that is, symplectic manifolds deformation equivalent to $\text{Hilb}^n(S)$ for a K3 surface $S$. In this case $L = 3U \oplus 2E_8(-1) \oplus (-2(n - 1))$. Here one has a better understanding of the map from the moduli space to the locally symmetric variety, thanks to the work of Markman [Mar2]. We show in Theorem 2.3 that in this case one may consider the quotient by the group $O(L, h)$ of automorphisms of $L$ that fix $h$ and act trivially on the discriminant group $L^\vee / L$.

To continue further we need to study the orthogonal groups that can arise. We do this in Section 3, where we mainly study the lattice $L_{2d} = 3U \oplus 2E_8(-1) \oplus (-2d)$. This leads us to a description of the possible types of polarisation for deformation $K3[n]$ manifolds. There are two special types, having only one orbit of polarising vectors.

For the rest of the paper we are concerned with the case $n = 2$ and with the simplest polarisation, namely the split type (see Definition 3.9), where the lattice $L_{h^\perp}$ is $L_{2,2d} = 2U \oplus 2E_8(-1) \oplus (-2) \oplus (-2d)$. Our main theorem, Theorem 4.1, states that every component of the corresponding moduli space is of general type as long as $d \geq 12$. O’Grady [OG4] studied the case $d = 1$ and showed that the moduli space is unirational. There seem to be very few other previous results about dimension 20 moduli spaces of orthogonal type. Voisin [Vo1] proved that one of them is birational to the moduli space of cubic fourfolds, and thus unirational, but the type of the polarisation in that case is not split. Another non-split case (with $d = 11$) was studied recently by Debarre and Voisin [DV]: again the moduli space is unirational. In the split case there are only nine possibly unirational moduli spaces (for $d = 9$ and $d = 11$ the Kodaira dimension is non-negative): for polarised K3 surfaces there are still forty-three such possibilities.

The proof of Theorem 4.1 is similar in style to the corresponding result for K3 surfaces proved in [GHS1] (see also [Vo2]), but there are many differences. We use the low-weight cusp form trick, which guarantees that once the stable orthogonal group $O(L_{2,2d})$ has a cusp form with suitable vanishing of weight less than the dimension of the moduli space then the components are of general type.

We construct the cusp form by means of the quasi pull-back of the Borcherds form, as in [GHS1]. To do so one requires a vector in $E_7$ orthogonal to at least 2 and at most 14 roots, of length $2d$.

Here there is a significant technical difficulty. The proof that these vectors exist involves estimating the number of ways of representing certain integers by various root lattices of odd rank. In Theorem 5.1 we give a new, clear, formulation of Siegel’s formula for this number in the odd rank case. It
may be expressed either in terms of Zagier $L$-functions or in terms of the H. Cohen numbers. This analytic estimate shows that the vectors we want exist for $d \geq 20$, and we can improve this bound slightly by means of a computer search.

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1 Irreducible symplectic manifolds

In this section we collect the necessary results concerning symplectic manifolds and their moduli. The main aim is to relate moduli spaces of polarised symplectic manifolds to quotients of homogeneous domains by an arithmetic group.

We begin with the basic definitions and facts about irreducible symplectic manifolds.

**Definition 1.1** A complex manifold $X$ is called an irreducible symplectic manifold if the following conditions are fulfilled:

(i) $X$ is a compact Kähler manifold;

(ii) $X$ is simply-connected;

(iii) $H^0(X, \Omega^2_X) \cong \mathbb{C}\sigma$ where $\sigma$ is an everywhere nondegenerate holomorphic 2-form.

Irreducible symplectic manifolds are also known as irreducible hyperkähler manifolds, and very often simply as symplectic manifolds. The symplectic surfaces are the K3 surfaces. In higher dimension the known examples are the Hilbert schemes $\text{Hilb}^n(S)$ of a K3 surface $S$ and deformations of them; generalised Kummer varieties and their deformations; and two examples of dimensions 6 and 10, constructed by O’Grady using moduli spaces of sheaves on abelian surfaces and K3 surfaces respectively ([OG1], [OG2]).

It follows immediately from the definition that $X$ must have even dimension $2n$ and that its canonical bundle $\omega_X$ is trivial. Moreover $h^{2,0}(X) = h^{0,2}(X) = 1$ and $h^{1,0}(X) = h^{0,1}(X) = 0$. By a result of Bogomolov ([Bog]), the deformation space of $X$ is unobstructed. This result was generalised to Ricci-flat manifolds by Tian ([Ti]) and Todorov ([Tod]), and algebraic proofs were given by Kawamata ([Ka]) and Ran ([Ran]) (see also [Fuj]). Since

$$T_{[0]} \text{Def}(X) \cong H^1(X, T_X) \cong H^1(X, \Omega^1_X)$$
the dimension of the deformation space is $b_2(X) - 2$.

The main discrete invariants for symplectic manifolds are the Beauville form (also known as the Beauville-Bogomolov form) and the Fujiki constant or Fujiki invariant. The Beauville form is an indivisible integral symmetric bilinear form on $H^2(X, \mathbb{Z})$ of signature $(3, b_2(X) - 3)$. Its role in the theory of irreducible symplectic manifolds is similar to the role of the intersection form for K3 surfaces. To define it, let $\sigma \in H^2(X, \mathbb{Z})$ be such that $\int_X (\sigma \sigma) = 1$ and define

$$q_X(\alpha) = \frac{n}{2} \int_X \alpha^2 (\sigma \sigma)^{n-1} + (1 - n) \left( \int_X \alpha \sigma^{n-1} \sigma \right) \left( \int_X \alpha^{n} \sigma^{n-1} \sigma \right).$$

After multiplication by a positive constant $\gamma$ the quadratic form $q_X = \gamma q_X'$ defines an indivisible, integral, symmetric bilinear form $(, )_X$ on $H^2(X, \mathbb{Z})$: this is the Beauville form. Clearly $(\sigma, \sigma)_X = 0$ and $(\sigma, \sigma)_X > 0$.

Let $v(\alpha) = \alpha^{2n}$ be given by the cup product. Then, by a result of Fujiki [Fuj, Theorem 4.7], there is a positive rational number $c$, the Fujiki invariant such that $v(\alpha) = cq_X(\alpha)^n$ for all $\alpha \in H^2(X, \mathbb{Z})$.

In [OG3] O'Grady introduced the notion of numerical equivalence among symplectic manifolds. Two symplectic manifolds $X$ and $X'$ of dimension $2n$ are said to be numerically equivalent if there exists an isomorphism $f: H^2(X, \mathbb{Z}) \cong H^2(X', \mathbb{Z})$ of abelian groups with $\int_X \alpha^{2n} = \int_{X'} f(\alpha)^{2n}$ for all $\alpha \in H^2(X, \mathbb{Z})$. The equivalence class of $X$ is called the numerical type of $X$, denoted by $N$. Clearly, two symplectic manifolds are numerically equivalent if they have the same Beauville form and Fujiki invariant. O'Grady [OG3, Section 2.1] showed that the converse is also true unless $b_2(X) = b_2(X') = 6$ and $n$ is even, in which case the numerical type determines $c_X$ but a priori one only has $q_X = \pm q_{X'}$. (There are, however, no known examples of irreducible symplectic manifolds with $b_2 = 6$.)

We fix an abstract lattice $L$ which is isomorphic to $H^2(X, \mathbb{Z})$ equipped with the Beauville form $(, )_X$ (the Beauville lattice) and consider its associated period domain

$$\Omega_L = \{ [w] \in \mathbb{P}(L \otimes \mathbb{C}) | (w, w) = 0, (w, \overline{w}) > 0 \}$$

which, since the signature is $(3, b_2(X) - 3)$, is connected. A marking of a symplectic manifold $X$ is an isomorphism $\psi: H^2(X, \mathbb{Z}) \cong L$ of lattices. We can associate to each marked symplectic manifold $(X, \psi)$ its period point $[\psi(\sigma)] \in \Omega_L$. Now let $f: X \rightarrow U$ be a representative of $\text{Def}(X)$. This means that $U$ is a polydisc, $X_0 := f^{-1}(0) \cong X$ and $f$ is a proper submersive map whose Kodaira-Spencer map

$$T_{f,0}: T_{U,0} \rightarrow H^1(X, T_X)$$
is an isomorphism. We can use the marking $\psi$ to define an isomorphism $\psi_U: R^2 f_* (\mathbb{Z}) \sim L_U$ (we shall tacitly shrink $U$ wherever necessary) and thus a period map

$$\varphi_U: U \rightarrow \Omega_L$$

$$t \mapsto [\psi_t(\sigma_{X_t})].$$

The local Torelli theorem for symplectic manifolds, proved by Beauville [Be], says that $\varphi_U$ is a local isomorphism (in the complex topology).

The surjectivity of the period map was proved by Huybrechts in [Huy1, Theorem 8.1]. To formulate his result we consider a fixed lattice $L$ which appears as the Beauville lattice of some symplectic manifold. Let $\mathcal{M}_L$ be the corresponding moduli space of marked symplectic manifolds, i.e. as a set $\mathcal{M}_L = \{(X, \psi: H^2(X, \mathbb{Z}) \sim L)/\approx \}$ where the equivalence relation $\approx$ is induced by $\pm f^*$ with $f: X \rightarrow X'$ a biholomorphic map. The space $\mathcal{M}_L$ admits a natural smooth complex structure which, however, is not Hausdorff.

The period map $\varphi: \mathcal{M}_L \rightarrow \Omega_L$ is a holomorphic map and Huybrechts has shown that every connected component of $\mathcal{M}_L$ maps surjectively onto $\Omega_L$. For a discussion of moduli of marked symplectic manifolds see the paper [Huy5] by Huybrechts.

The situation improves considerably when one considers moduli of polarised symplectic manifolds. A polarisation on a symplectic manifold $X$ is the choice of an ample line bundle $\mathcal{L}$ on $X$. Since the irregularity of $X$ is 0 this is the same as the choice of a class $h \in H^2(X, \mathbb{Z})$ representing an ample line bundle on $X$. Clearly $q_X(h) > 0$.

Conversely, Huybrechts has shown ([Huy1, Theorem 3.11]: see also [Huy2, Theorem 2]) that a symplectic manifold $X$ is projective if and only if there exists a class $h \in H^2(X, \mathbb{Z}) \cap H^{1,1}(X)$ with $q_X(h) > 0$. It should be noted, however, that neither line bundle associated to $\pm h$ need be ample. There is, however, a small deformation of the pair $(X, h)$ with this property.

We now fix an abstract lattice $L$ of rank $b_2 = b_2(X)$ such that $H^2(X, \mathbb{Z}) \cong L$ and let $h \in L$ be a primitive element with $h^2 > 0$. Then the lattice

$$L_{h\perp} = h_{\perp}^L < L$$

has signature $(2, b_2 - 3)$. It defines a homogeneous domain, which in this case has two connected components

$$\Omega_{L_{h\perp}} = \mathcal{D}(L_{h\perp}) \cup \mathcal{D}'(L_{h\perp}).$$

(1)

If $(X, h)$ is a pair with $h \in H^2(X, \mathbb{Z}) \cap H^{1,1}(X)$ and $\psi: H^2(X, \mathbb{Z}) \rightarrow L$ is a marking then the period point $[\psi(\sigma)] \in \Omega_{L_{h\perp}}$. Hence for every deformation $X' \rightarrow U$ of the pair $(X, h)$ the period map defines a holomorphic map $\varphi_U: U \rightarrow \Omega_{L_{h\perp}}$.

In this paper we are interested in the moduli spaces of polarised symplectic manifolds. We shall fix the dimension $2n$ and the numerical type $N$ of
the symplectic manifolds that we consider. We have already remarked that this determines the Beauville lattice and Fujiki invariant unless \( b_2 = 6 \) and \( n \) is even, in which case the quadratic form is only determined up to sign. We shall consider polarised symplectic manifolds \((X,h)\) of fixed numerical type and given value \( q_X(h) = d > 0 \). The degree of the associated line bundle \( L \) is \( \deg(L) = h^{2n} = cd^n \) where \( c \) is the Fujiki invariant. Instead of working with the (geometric) degree of a polarisation we prefer to work with the number \( d \), which we will call the Beauville degree of the polarisation. We first note the following variant of a result of Huybrechts [Huy4, Theorem 4.3], which is itself an application of the finiteness theorem of Kollár and Matsusaka [KM, Theorem 3].

**Proposition 1.2** For fixed numerical type there are only finitely many deformation types of polarised symplectic manifolds \((X,h)\) of dimension \( 2n \) and given Beauville degree \( d = q_X(h) > 0 \).

*Proof.* Since the numerical type determines the Fujiki invariant \( c \) our choices also fix the degree \( h^{2n} = cq_X(h)^n > 0 \). The result follows immediately from [Huy4, Corollary 26.17]. \( \square \)

Now we define the moduli spaces we are interested in. We first fix a possible Hilbert polynomial, say \( P(m) \). Note that this is more than fixing the degree of the polarisation. By Matsusaka’s big theorem we can find a constant \( m_0 \) such that for all polarised manifolds \((X,L)\) with Hilbert polynomial \( P(m) \) the line bundles \( L^\otimes m \) are very ample for \( m \geq m_0 \) and have no higher cohomology. Then we have embeddings \( \varphi|_{L^\otimes m_0}: X \to \mathbb{P}^{N-1} \) where \( N = h^0(X,L^\otimes m_0) = P(m_0) \). Such an embedding depends on the choice of a basis of \( H^0(X,L^\otimes m_0) \). Let \( H \) be an irreducible component of the Hilbert scheme \( \text{Hilb}_P(\mathbb{P}^{N-1}) \) that contains at least one point \( \eta \in H \) corresponding to a symplectic manifold \( X_\eta \). We denote by \( H_{sm} \) the open part of \( H \) parametrising smooth varieties. The following lemma is well known. We include a proof since we are not aware of a suitable reference.

**Lemma 1.3** \( H_{sm} \) has the following properties:

(i) Every point in \( H_{sm} \) parametrises a symplectic manifold;

(ii) \( H_{sm} \) is smooth.

*Proof.* Claim (i) follows from Beauville’s classification theorem [Be, §5, Théorème 2]: the universal family \( X_{sm} \) over \( H_{sm} \) is a flat family of projective (and hence compact Kähler) manifolds which are simply-connected with trivial canonical bundle. Moreover, since the second Betti number is constant \( h^{2,0}(X) = 1 \) for every fibre by semi-continuity.
This can be proved along the lines of [Sz, Theorem 1.3]. The long exact sequence of the normal bundle sequence yields

\[ \cdots \rightarrow H^0(X, N_{X/P^{N-1}}) \xrightarrow{\alpha} H^1(X, T_X) \rightarrow H^1(X, T_{P^{N-1}|X}) \rightarrow \cdots \]

The image of \( \alpha \) is contained in the hyperplane \( V_h = h^\perp \subset H^1(X, T_X) \cong H^1(X, \Omega^1_X) \), which corresponds to deformations of the pair \( (X, h) \) where \( h = c_1(L) = \mathcal{O}_X(1) \). Since \( H^1(X, T_{P^{N-1}|X}) \) is 1-dimensional (which follows from the restriction of the Euler sequence to \( X \)) the image of \( \alpha \) is equal to \( V_h \) and hence the Hilbert scheme is unobstructed and thus smooth. \( \square \)

**Definition 1.4** Let \( L \) be a lattice. The stable orthogonal group \( \tilde{O}(L) \) is defined by

\[ \tilde{O}(L) = \{ g \in O(L) \mid g(l^\vee) \equiv l^\vee \mod L \text{ for all } l^\vee \in L^\vee \}. \]  

We shall also need

\[ \tilde{O}(L) = \{ g \in O(L) \mid g(l^\vee) \equiv \pm l^\vee \mod L \text{ for all } l^\vee \in L^\vee \}. \]  

For a primitive element \( h \in L \) with \( h^2 = d > 0 \), we define the groups

\[ O(L, h) = \{ g \in O(L) \mid g(h) = h \} \]  

and

\[ \tilde{O}(L, h) = \{ g \in \tilde{O}(L) \mid g(h) = h \}. \]

For any subgroup \( \Gamma \subset O(L) \) we define the projective group \( P\Gamma = \Gamma/(\pm 1) \).

If \( L \) is indefinite we define \( \Gamma^+ \) to be the subgroup of \( \Gamma \) of elements with real spin norm 1.

There are two ways to choose the definition of the spin norm. We have chosen it in such a way that any \( -2 \)-reflection has spin norm 1.

We can consider \( O(L, h) \) and \( \tilde{O}(L, h) \) as subgroups of \( O(L_{h^\perp}) \), where \( L_{h^\perp} \) is, as usual, the lattice perpendicular to \( h \) in \( L \). We shall discuss the relationships among these three groups in Section 3.

Note that in our case the lattice \( L \) has signature \( (3, b_2 - 3) \) and hence \( L_{h^\perp} \) has signature \( (2, b_2 - 3) \). Thus the lattice \( L_{h^\perp} \) determines a homogeneous domain \( \Omega_h = \Omega_{L_{h^\perp}} \) of type IV on which the three groups act, and if \( \Gamma < O(L_{h^\perp}) \) then \( \Gamma^+ \) is the subgroup of \( \Gamma \) that preserves the component \( D \).

The following theorem is crucial for the rest of the paper. Viehweg’s results on moduli spaces [ViI] together with Proposition [12] give us the existence of moduli spaces of polarised irreducible symplectic manifolds of fixed numerical type. More importantly, this result allows us to relate these moduli spaces to modular varieties, in this case to quotients of a homogeneous domain of type IV by a suitable arithmetic group. (Both the domain and the group depend on the moduli problem in question.)
Theorem 1.5 There exists a quasi-projective coarse moduli space \( M_{2n,N,d} \) parametrising primitively polarised symplectic manifolds of dimension \( 2n \), numerical type \( N \) and Beauville degree \( d \). We choose any one of the irreducible components of \( M_{2n,N,d} \) and denote it by \( M_d \). Such a choice determines a primitive vector \( h \in L \) (or possibly \( h \in L(-1) \) if \( b_2 = 6 \) and \( n \) is even) with \( q(h) = d \) such that there is a map

\[ \varphi: M_d \rightarrow (O(L, h) \setminus \Omega_h)^0. \]

Here \((O(L, h) \setminus \Omega_h)^0\) is a connected component of \( O(L, h) \setminus \Omega_h \). The map \( \varphi \) is a morphism of quasi-projective varieties which is dominant and finite onto its image.

Proof. Proposition 1.2 shows that there are only finitely many possible Hilbert polynomials for a given choice of the discrete data \( 2n \), \( N \) and \( d \). It then follows from Viehweg’s work [Vi, Theorem 1.13] and the discussion there that the moduli spaces in question exist: indeed, every component \( M_d \) of \( M_{2n,N,d} \) is a quotient of the form \( \text{SL}(N, \mathbb{C}) \setminus H_{\text{sm}} \) for some component \( H \) of a suitable Hilbert scheme (see the discussion of Lemma 1.3).

We now want to relate the components \( M_d \) to quotients of the form \( O(L, h) \setminus \Omega_h \). For this we want to construct a map \( \tilde{\varphi}: H_{\text{sm}} \rightarrow O(L, h) \setminus \Omega_h \) and then argue that it factors through the quotient by \( \text{SL}(N, \mathbb{C}) \). We first observe that every component \( H \) determines an \( O(L) \)-orbit of primitive vectors \( h \in L \) with \( q(h) = d \). Indeed, choosing a local marking \( \psi_t \) near a given point in \( H_{\text{sm}} \) we obtain a vector \( h_t = \psi_t(c_1(O_X(1))) \) with \( q(h_t) = d \), and any two local markings differ by an element of \( O(L) \). Since \( H_{\text{sm}} \) is connected and the number of \( O(L) \)-orbits is finite this associates to each \( H_{\text{sm}} \) a unique \( O(L) \)-orbit. Let \( h \) be a representative of the orbit defined by \( H_{\text{sm}} \). We shall be interested only in \( h \)-markings, that is, markings \( \psi \) with \( \psi(c_1(O_X(1))) = h \). They exist locally on all of \( H_{\text{sm}} \), and an \( h \)-marking on an open set \( U \subset H_{\text{sm}} \) defines, via the period map, a holomorphic map \( \varphi_U: U \rightarrow \Omega_h \). Two \( h \)-markings differ by an element of \( O(L) \), so we obtain a holomorphic map \( \tilde{\varphi}: H_{\text{sm}} \rightarrow O(L, h) \setminus \Omega_h \).

Assume that \( M \in \text{SL}(N, \mathbb{C}) \) maps \( (X, O_X(1)) \) to \( (X', O_{X'}(1)) \). Given \( h \)-markings \( \psi: H^2(X, \mathbb{Z}) \rightarrow L \) and \( \psi': H^2(X', \mathbb{Z}) \rightarrow L \) there exists an element \( g \in O(L, h) \) with \( \psi \circ M^* = g \circ \psi' \). This shows that the map \( \tilde{\varphi} \) factors through the quotient by \( \text{SL}(N, \mathbb{C}) \), giving the required map

\[ \varphi: M_d \rightarrow (O(L, h) \setminus \Omega_h)^0. \]

Next we want to show that the map \( \varphi \) is a morphism of quasi-algebraic varieties. This can be deduced from a theorem of Borel [B] which says the following: if \( Y \) is a quasi-projective variety and \( f: Y \rightarrow \Gamma \setminus \Omega \) a holomorphic map to an arithmetic quotient of a homogeneous domain, where \( \Gamma \) is torsion free, then \( f \) is a morphism of quasi-projective varieties. Here \( \Gamma \setminus \Omega \)
carries the natural structure as a quasi-projective variety, which comes from the Baily-Borel compactification. Although one cannot apply this theorem immediately, as \(O(L, h)\) will in general not be torsion free, the difficulty can be avoided by using level structures. The argument given by Hassett in [Ha Proposition 2.2.2] in the special case of cubic fourfolds carries over without difficulties.

Finally we want to prove that \(\phi\) is dominant and has finite fibres. Since \(\phi\) is a morphism of quasi-projective varieties it is enough to show that \(\phi\) has no positive-dimensional fibres and that the image has the same dimension as the period domain. We proceed by following Szendrői’s arguments in [Sz]. As in [Sz Lemma 2.7] one can construct a finite étale covering \(H'_{\text{sm}} \rightarrow H_{\text{sm}}\) with the property that the action of \(\text{SL}(N, \mathbb{C})\) lifts to a free action on \(H'_{\text{sm}}\) as well as to an action on the pullback \(\mathcal{Y}_{\text{sm}} \rightarrow H'_{\text{sm}}\) of the universal family \(\mathcal{X}_{\text{sm}} \rightarrow H_{\text{sm}}\). Dividing by the action of \(\text{SL}(N, \mathbb{C})\) one obtains a quotient family over a base \(Z_{\text{sm}}\) which is smooth and finite over the moduli space. By the infinitesimal Torelli theorem the period map on \(Z_{\text{sm}}\) is open with discrete fibres near every point of \(Z_{\text{sm}}\). Since the group \(O(L, h)\) acts properly discontinuously on the domain \(\Omega_h\), the induced morphism \(Z_{\text{sm}} \rightarrow O(L, h) \setminus \Omega_h\) is dominant and has no positive-dimensional fibres and hence the same also holds for \(\phi\).

\(\Box\)

**Remark 1.6** The map \(\phi: M_d \rightarrow (O(L, h) \setminus \Omega_h)^0\) will in general not be surjective as there are period points in \(\Omega_h\) which parametrise pairs \((X, h)\) where \(h\) is not ample.

This phenomenon already occurs for K3 surfaces. Unlike in the K3 case it is, however, not clear which open part of the period domain belongs to ample divisors. There are some results about this in special cases, due to Hassett and Tschinkel [HT].

We shall use Theorem 1.5 in Section 4 to prove general type results for some moduli spaces of symplectic manifolds by proving that the quotients \(O(L, h) \setminus \Omega_h\) are of general type.

# 2 Deformation \(K3^{[n]}\) manifolds and monodromy

For the remainder of the paper we concentrate on a special case.

**Definition 2.1** A deformation \(K3^{[n]}\) manifold is a symplectic manifold that is deformation equivalent to \(\text{Hilb}^n(S)\) for some K3 surface \(S\).

(Compare the definition of numerical K3\([2]\) in [OG3].) If \(X\) is a deformation \(K3^{[n]}\) manifold then \(H^2(X, \mathbb{Z}) \cong L_{2n-2}\) (as a lattice with the Beauville form), where for any \(t \in \mathbb{N}\) we put

\[
L_{2t} = 3U \oplus 2E_8(-1) \oplus (-2t).
\]  \((6)\)
For deformation $\text{K3}^{[n]}$ manifolds, the numerical type is determined completely by the dimension $2n$, and the (Beauville) degree of a polarisation is always even. The Fujiki invariant is $\frac{(2n)!}{2^n}$.

We study deformation $\text{K3}^{[n]}$ manifolds by using monodromy operators, whose theory was developed by Markman [Mar1, Mar2]. We consider a flat family $\pi: \mathcal{X} \rightarrow B$ of compact complex manifolds with fibre $X$ over the point $b \in B$. Associated to such a family we obtain a monodromy representation

$$\pi_1(B, b) \rightarrow \text{Aut}(H^*(X, \mathbb{Z})).$$

We define the group of monodromy operators to be the subgroup $\text{Mon}(X)$ of $\text{Aut}(H^*(X, \mathbb{Z}))$ generated by the image of all monodromy representations. If we restrict to the second cohomology, we obtain a representation $\pi_1(B, b) \rightarrow \text{Aut}(H^2(X, \mathbb{Z}))$ and correspondingly a subgroup $\text{Mon}^2(X) \subset \text{Aut}(H^2(X, \mathbb{Z}))$. If $X$ is a symplectic manifold then monodromy transformations preserve the Beauville form and we obtain a subgroup $\text{Mon}^2(X) \subset O(H^2(X, \mathbb{Z}))$.

Let $\text{Ref}(X)$ be the subgroup of $O(H^2(X, \mathbb{Z}))$ generated by $-2$-reflections and by the negatives of $+2$-reflections. By the choice of spin norm made in Definition 1.4, this is a subgroup of $O^+(H^2(X, \mathbb{Z}))$.

**Theorem 2.2 (Markman [Mar2, Theorem 1.2].)** If $X$ is a deformation $\text{K3}^{[n]}$ manifold then $\text{Mon}^2(X) = \text{Ref}(X)$.

Using a marking $\psi: H^2(X, \mathbb{Z}) \rightarrow L$ we can think of $\text{Mon}^2(X)$ as a subgroup of $O^+(L_{2n-2})$. Since $\text{Mon}^2(X)$ is a normal subgroup we obtain a well-defined subgroup $\text{Mon}^2(L_{2n-2}) = \text{Ref}(L_{2n-2}) = \text{Ref}(X) \subset O^+(L_{2n-2})$.

It follows from a result of Kneser [Kn, Satz 4] or from [Mar1, Lemma 4.10] that the groups satisfy

$$\text{Ref}(L_{2n-2}) = \widehat{O}^+(L_{2n-2})$$

(see Definition 1.4). Note that the assumptions of Kneser’s theorem are fulfilled since $L_{2n-2}$ contains three copies of $U$.

Unlike in the case of K3 surfaces, for fixed degree $2d$ there is not a unique $O^+(L_{2n-2})$-orbit of primitive vectors $h$ with $h^2 = 2d$. We shall address this question in Section 3. Hence the moduli space of deformation $\text{K3}^{[n]}$ manifolds with a primitive polarisation of degree $2d$ will in general have more than one component.

**Theorem 2.3** Let $\mathcal{M}_{2d}^{[n]}$ be an irreducible component of the moduli space of deformation $\text{K3}^{[n]}$ manifolds with a primitive polarisation of degree $2d$. Then the map $\varphi$ from Theorem 1.5 above, factors through the finite cover
\[ \tilde{O}^+ (L_{2n-2}, h) \setminus D_h \to O^+ (L_{2n-2}, h) \setminus D_h; \text{ that is, there is a commutative diagram} \]

\[ \begin{array}{ccc}
\mathcal{M}^{[n]}_{2d} & \xrightarrow{\hat{\varphi}} & \tilde{O}^+ (L_{2n-2}, h) \setminus D_h \\
\varphi \downarrow & & \downarrow \\
O^+ (L_{2n-2}, h) \setminus D_h
\end{array} \]

**Proof.** Recall from the proof of Theorem [1.5] that \( \mathcal{M}^{[n]}_{2d} = \text{SL}(N, \mathbb{C}) \setminus H_{\text{sm}} \) for some suitable open part of a component \( H \) of the Hilbert scheme. We choose a base point in \( H_{\text{sm}} \) and denote the corresponding symplectic variety by \( X_0 \). Choose an \( h \)-marking \( \psi_0 : (H^2(X_0, \mathbb{Z}), c_1(\mathcal{O}_{X_0(1)})) \to (L_{2n-2}, h) \). Now let \( Y \) be a variety corresponding to another point in \( H \) and choose a path \( \sigma_Y \) from \( X_0 \) to \( Y \). Transporting the marking \( \psi_0 \) along this path we obtain an \( h \)-marking \( \psi_{\sigma_Y} : (H^2(Y, \mathbb{Z}), c_1(\mathcal{O}_Y(1))) \to (L_{2n-2}, h) \). Clearly this marking will depend on the path \( \sigma_Y \). Let \( \tau_Y \) be another path from \( X_0 \) to \( Y \) and \( \psi_{\tau_Y} \) the corresponding marking. Then \( \tau_Y \circ \sigma_Y^{-1} \) is a closed path based at \( Y \) and induces an automorphism \( f^* = \psi_{\sigma_Y}^{-1} \circ \psi_{\tau_Y} \in \text{Mon}^2(Y) \). Let \( f' = \psi_{\sigma_Y} \circ f^* \circ \psi_{\sigma_Y}^{-1} \in \text{Mon}^2(L_{2n-2}) \). Then \( f' \circ \psi_{\sigma_Y} = \psi_{\sigma_Y} \circ f^* = \psi_{\tau_Y} \). This shows that we have a morphism

\[ \varphi' : H_{\text{sm}} \to (\text{Mon}^2(L_{2n-2}) \cap O^+ (L_{2n-2}, h)) \setminus D_h = \tilde{O}^+ (L_{2n-2}, h) \setminus D_h \]

where the last equality follows from Theorem [2.2] and equation [7].

We next claim that \( \varphi' \) factors through \( \mathcal{M}^{[n]}_{2d} \). For this let \( g \in \text{SL}(N, \mathbb{C}) \) be an element which maps \( Y \) to \( Z \). Let \( \sigma_Y \) and \( \sigma_Z \) be paths from \( X_0 \) to \( Y \) and \( Z \) respectively, with corresponding markings \( \psi_{\sigma_Y} \) and \( \psi_{\sigma_Z} \). We now consider the path \( \sigma_Z \circ \sigma_Y^{-1} \) from \( Y \) to \( Z \). Using the element \( g \) to identify \( Y \) and \( Z \) makes this a closed path. We can now argue as above and conclude that \( \psi_{\sigma_Y} \circ g^* \circ \psi_{\sigma_Z}^{-1} \in \text{Mon}^2(L_{2n-2}) \cap O^+ (L_{2n-2}, h) = \tilde{O}^+ (L_{2n-2}, h) \).

(Strictly speaking we need a complex family to argue that this element is in \( \text{Mon}^2(L_{2n-2}) \), but this can easily be achieved by a complex thickening of the closed path.)

We can put \( \tilde{O}^+ (L_{2n-2}, h) \) in the formulation of the theorem because \( P\tilde{O}^+ (L_{2n-2}, h) \cong P\tilde{O}^+ (L_{2n-2}, h) \), and the groups act on the symmetric space through their projectivisations. \( \square \)

**Remark 2.4** The lifting of the map \( \varphi \) to \( \hat{\varphi} \) is not unique. Two markings \( \psi_0 \) and \( \psi_1 \) define the same lifting if and only if \( \psi_0 \circ \psi_1^{-1} \) is trivial in \( \text{PO}^+ (L_{2n-2}, h) / P\tilde{O}^+ (L_{2n-2}, h) \), so the different liftings are classified by the quotient \( \text{PO}^+ (L_{2n-2}, h) / P\tilde{O}^+ (L_{2n-2}, h) \). We shall compute the index of \( \tilde{O}^+ (L_{2n-2}, h) \) in \( O^+ (L_{2n-2}, h) \) below (Proposition [3.12]), in almost all cases.
Theorem 2.3 should also be compared to Markman’s consideration of the non-polarised case in [Mar2, Section 4.2].

**Remark 2.5** As in [Mar2] we can conclude from Theorem 2.3 that the global Torelli theorem for polarised deformation K3\[^n\] manifolds fails whenever 
\[ \text{PO}^+(L_{2n-2}, h) : \text{PO}^+(L_{2n-2}, h) > 1. \]
This can occur: see Proposition 3.12 below.

With Remark 2.5 in mind we pose the following question.

**Question 2.6** Is it true that for every \( \text{O}^+(L_{2n-2}) \)-orbit of some primitive vector \( h \) with \( h^2 = 2d > 0 \) the part of the moduli space \( M_{2n,N,2d} \) corresponding to polarisations in the orbit of \( h \) is irreducible and that the map \( \tilde{\varphi} \) has degree 1?

A positive answer to both parts of Question 2.6 could be viewed as the correct version of the global Torelli theorem for deformation K3\[^n\] manifolds.

**Remark 2.7** For every class of symplectic manifolds, Theorem 1.5 remains true if we consider the monodromy group instead of the orthogonal group.

### 3 Orthogonal groups

Let \( L \) be an even lattice. By lattice (or sublattice) we always mean a non-degenerate lattice (or sublattice). We denote the discriminant group of \( L \) by \( D(L) = L^\vee / L \). This carries an induced quadratic form with values in \( \mathbb{Q} / 2\mathbb{Z} \). If \( g \in O(L) \) we denote by \( \bar{g} \) its image in \( O(D(L)) \).

Let \( S \) be a primitive sublattice of \( L \): we are mainly interested in the case \( S = L_h \) for some \( h \in L \) with \( h^2 \neq 0 \), but we want to consider this more general situation. Analogously to Definition 1.4 we define the groups

\[
O(L, S) = \{ g \in O(L) \mid g | S \in \tilde{O}(S) \} \quad \text{and} \quad \tilde{O}(L, S) = O(L, S) \cap \tilde{O}(L).
\]

Note that \( O(L, Z h) = O(L, h) \) if \( h^2 \neq \pm 2 \).

Let \( S^\perp \) be the orthogonal complement of \( S \) in \( L \). We have

\[
S^\perp \oplus S < L < L^\vee < (S^\perp)^\vee \oplus S^\vee.
\]

The overlattice \( L \) is defined by the finite subgroup

\[
H = L/(S^\perp \oplus S) < (S^\perp)^\vee / S^\perp \oplus S^\vee / S = D(S^\perp) \oplus D(S)
\]

which is an isotropic subgroup of \( D(S^\perp) \oplus D(S) \). Following [Nik] we consider the projections

\[
p_S : H \to D(S), \quad p_{S^\perp} : H \to D(S^\perp).
\]
Using the definitions and the fact that the lattices $S$ and $S^\perp$ are primitive in $L$ one can show (see [Nik Prop. 1.5.1]) that these projections are injective and moreover that if $d_S \in p_S(H)$ then there is a unique $d_{S^\perp} \in p_{S^\perp}(H)$ such that $d_S + d_{S^\perp} \in H$.

**Lemma 3.1** $\alpha \in O(S^\perp)$ can be extended to $O(L)$ if and only if

$$\tilde{\alpha}(p_{S^\perp}(H)) = p_{S^\perp}(H)$$

and there exists $\beta \in O(S)$ such that $p_{S^\perp}^{-1} \circ \tilde{\beta} \circ p_S = p_{S^\perp}^{-1} \circ \alpha \circ p_{S^\perp}$.

This is a reformulation of [Nik Corollary 1.5.2]. The following is a particular case.

**Lemma 3.2** Let $S$ be a primitive sublattice of an even lattice $L$.

(i) $g \in O(L, S)$ if and only if $g(S) = S$, $\tilde{g}|_{D(S)} = \text{id}$ and $\tilde{g}|_{p_{S^\perp}(H)} = \text{id}$.

(ii) $\alpha \in O(S^\perp)$ can be extended to $O(L, S)$ if and only if $\tilde{\alpha}|_{p_{S^\perp}(H)} = \text{id}$.

(iii) If $p_{S^\perp}(H) = D(S^\perp)$ then $O(L, S)|_{S^\perp} \cong \tilde{O}(S^\perp)$.

(iv) Assume that the projection $O(S^\perp) \to O(D(S^\perp))$ is surjective. Then

$$O(L, S)|_{S^\perp}/\tilde{O}(S^\perp) \cong \{ \tilde{\gamma} \in O(D(S^\perp)) \mid \tilde{\gamma}|_{p_{S^\perp}(H)} = \text{id} \}.$$ 

**Remark 3.3** Let $g \in O(L, S)$. Then $\tilde{g}|_{p_{S^\perp}(H)} = \text{id}$ is equivalent to $\tilde{g}|_H = \text{id}$ or to $\tilde{g}|_{H^\vee} = \text{id}$, where $H^\vee = ((S^\perp)^\vee \oplus S^\vee)/L^\vee$. The condition $\tilde{g}|_{H^\vee} = \text{id}$ is equivalent to the following: for any $v \in (S^\perp)^\vee$ we have $g(v) - v \in (S^\perp)^\vee \cap L^\vee$.

But $(S^\perp)^\vee \cap L^\vee$ might be larger than $S^\perp$. This shows in terms of the dual lattices that $\tilde{g}|_{p_{S^\perp}(H)} = \text{id}$ is weaker than $g|_{S^\perp} \in \tilde{O}(S^\perp)$.

**Corollary 3.4** If $|H| = |\det S^\perp|$ then $O(L, S)|_{S^\perp} \cong \tilde{O}(S^\perp)$.

**Proof.** This follows from the injectivity of $p_{S^\perp}$ on $H$ and from Lemma [3.2](iii). For example, the condition of the corollary is true if $L$ is an even unimodular lattice and $S$ is any primitive sublattice of $L$. 

If $l \in L$ its divisor $\text{div}(l)$ is the positive generator of the ideal $(l, L) \subset \mathbb{Z}$. Therefore $l^* = l/\text{div}(l)$ is a primitive element of the dual lattice $L^\vee$ and $\text{div}(l)$ is a divisor of $\det(L)$. We recall the following classical criterion of Eichler (see [E1 §10]).

**Lemma 3.5** Let $L$ be a lattice containing two orthogonal isotropic planes. Then the $\tilde{O}(L)$-orbit of a primitive vector $l \in L$ is determined by two invariants: by its length $l^2 = (l, l)$ and its image $l^* + L$ in the discriminant group $D(L)$.
We consider the special lattice \( L_{2t} = 3U \oplus 2E_8(-1) \oplus \langle -2t \rangle \) defined in Equation (6) above. We shall need this for the application in Section 4. It has signature (3, 20). We denote a generator of the 1-dimensional sublattice \( \langle -2t \rangle \) by \( l_t \), so \( l_t^2 = -2t \), and we denote by \( h_d \) a primitive vector of length \( 2d \). Note that \( \text{div}(h_d) \) is a common divisor of \( 2d \) and \( 2t = \det(L_{2t}) \).

We now investigate the groups \( O(L_{2t}, h_d) \) and \( \tilde{O}(L_{2t}, h_d) \). In Proposition 3.6 we count the \( \tilde{O}(L_{2t}) \)-orbits of the polarisation vectors \( h_d \). This number is not always 1. Thus the situation here is different from the case of K3 surfaces, because there the degree of the polarisation determines the orbit of the polarisation vector and here in general it does not. This fact is significant for future studies dealing with classes of polarisations not covered in this paper.

**Proposition 3.6** Let \( h_d \in L_{2t} \) be primitive of length \( 2d > 0 \) and \( \text{div}(h_d) = f \). We put

\[
g = \left( \frac{2d}{f}, \frac{2f}{f} \right), \quad w = (g, f), \quad g = wg_1, \quad f = wf_1.
\]

Then

\[
2t = fg t_1 = w^2 f_1 g_1 t_1 \quad \text{and} \quad 2d = f gd_1 = w^2 f_1 g_1 d_1
\]

where \( (t_1, d_1) = (f_1, g_1) = 1 \).

(i) If \( g_1 \) is **even**, then such an \( h_d \) exists if and only if \( (d_1, f_1) = (f_1, t_1) = 1 \) and \( -d_1/t_1 \) is a quadratic residue modulo \( f_1 \). Moreover the number of \( \tilde{O}(L_{2t}) \)-orbits of \( h_d \) with fixed \( f \) (if at least one \( h_d \) exists) is equal to

\[
w_+(f_1) \phi(w_-(f_1)) \cdot 2^{\rho(f_1)},
\]

where \( w = w_+(f_1)w_-(f_1) \) and \( w_+(f_1) \) is the product of all powers of primes dividing \( (w, f_1) \), \( \rho(n) \) is the number of prime factors of \( n \) and \( \phi(n) \) is the Euler function.

(ii) If \( g_1 \) is **odd**, and \( f_1 \) is **even** or \( f_1 \) and \( d_1 \) are both **odd**, then such an \( h_d \) exists if and only if \( (d_1, f_1) = (t_1, 2f_1) = 1 \) and \( -d_1/t_1 \) is a quadratic residue modulo \( 2f_1 \). The number of \( \tilde{O}(L_{2t}) \)-orbits of such \( h_d \) is equal to

\[
w_+(f_1) \phi(w_-(f_1)) \cdot 2^{\rho(f_1/2)} \quad \text{if } f_1 \equiv 0 \mod 2
\]

and to

\[
w_+(f_1) \phi(w_-(f_1)) \cdot 2^{\rho(f_1)} \quad \text{if } f_1 \equiv d_1 \equiv 1 \mod 2.
\]
(iii) If \( g_1 \) and \( f_1 \) are both odd and \( d_1 \) is even, then such an \( h_d \) exists if and only if \((d_1, f_1) = (t_1, 2f_1) = 1, -d_1/(4t_1) \) is a quadratic residue modulo \( f_1 \) and \( w \) is odd. The number of \( \hat{O}(L_{2t}) \)-orbits of such \( h_d \) is equal to
\[
w_+(f_1)\phi(w_-(f_1)) \cdot 2^{\rho(f_1)}.
\]

(iv) For \( c \) a suitable integer, determined mod \( f \) and satisfying \((c, f) = 1, \) and \( b = (d + c^2t)/f^2, \) we have
\[
(h_d)^{1}_{1} \cong 2U \oplus 2E_8(-1) \oplus B \quad \text{with} \quad B = \begin{pmatrix} -2b & c^2t \\ c^2t & -2t \end{pmatrix}.
\]

The form \( B \) is a negative definite binary quadratic form of determinant \( 4df^2/f^2. \) The greatest common divisor of the elements of \( B \) is equal to \( \varphi(\frac{2b}{g_1}, w). \)

**Proof.** A primitive vector \( h_d \) with \((h_d, L_{2t}) = fZ \) can be written
\[
h_d = fv + cl_t
\]
where \( v \in 3U \oplus 2E_8(-1). \) The coefficient \( c \) is coprime to \( f \) because \( h_d \) is primitive. According to Eichler’s criterion (Lemma 3.5) the \( \hat{O}(L_{2t}) \)-orbit of \( h_d \) is uniquely determined by \( h_d^* \equiv f^* \mod L_{2t}. \) Therefore it is determined by \( c \mod f \) because the discriminant group of \( L_{2t} \) is cyclic.

We put \( v^2 = 2b. \) Then \( 2d = 2bf^2 - 2c^2t, \) or
\[
2f_1b = g_1(d_1 + c^2t_1)
\]
with \((f_1, g_1) = (t_1, d_1) = (c, f_1) = 1. \) If \( c \) is coprime to \( f \) and satisfying Equation (8) exists, then because \((f_1, t_1)|g_1d_1 \) we must have \((f_1, t_1) = 1, \) and similarly we must have \((f_1, d_1) = 1. \)

(i) First we consider the case when \( g_1 \) is even. Equation (8) is equivalent to the congruence
\[
t_1c_1^2 \equiv -d_1 \mod f_1, \quad c_1 \equiv c \mod f_1. \tag{9}
\]
If \( g_1 \) is even, then \( f_1 \) is odd. Since \((t_1, f_1) = (d_1, f_1) = 1, -d_1/t_1 \) mod \( f_1 \) is invertible modulo \( f_1. \) If \(-d_1/t_1 \) is not a quadratic residue modulo \( f_1 \) then the congruence (9) has no solutions, so we assume that \(-d_1/t_1 \) is a quadratic residue modulo \( f_1. \) Because \( f_1 \) is odd, the number of solutions \( c_1 \) of (9) taken modulo \( f_1 \) is equal to
\[
\#\{x \mod f_1 \mid x^2 \equiv 1 \mod f_1 \} = 2^{\rho(f_1)}.
\]

Let us calculate the number of solutions \( c \) modulo \( f \) where \( f = wf_1. \) Any solution \( c_1 \) is coprime to \( f_1. \) Let us put
\[
c = c_1 + (x + yw_-(f_1))f_1
\]

15
where $x$ is taken mod $w_-(f_1)$ and $y$ is taken mod $w_+(f_1)$.

We note that $(f_1, w_-(f_1)) = 1$. We have $(c, w_{f_1}) = 1$ if and only if $(c + x f_1, w_-(f_1)) = 1$. For any fixed $c_1$ the numbers $c_1 + x f_1$ form the full residue system modulo $w_-(f_1)$ if $x$ runs modulo $w_-(f_1)$. Therefore for any fixed $c_1$ there are exactly $w_+(f) \phi(w_-(f_1))$ solutions $c$ modulo $f = f_1 w$ such that $c \equiv c_1 \mod f_1$ and $(c, f) = 1$. This finishes the proof of (i).

(ii) Consider the case when $g_1$ is odd. In this case $t_1$ is also odd, since $(g_1, 2 f_1) = 1$ so $d_1 + c^2 t_1 \equiv 0 \mod 2 f_1$: so if $t_1$ is even then $d_1$ is also even.

If $f_1$ is even, then because $f_1^2$ is divisible by $2 f_1$ Equation (8) is equivalent to the congruence

$$t_1 c_1^2 \equiv -d_1 \mod 2 f_1, \quad c_1 \equiv c \mod f_1.$$

Since $(f_1, d_1) = 1$ we know that $d_1$ is odd. Therefore

$$\# \{c_1 \mod f_1 \mid c_1^2 \equiv -d_1/t_1 \mod 2 f_1\} = 2^\delta(f_1/2)$$

if $-d_1/t_1$ is a quadratic residue mod $2 f_1$. The rest is similar to the case (i).

If $f_1$ and $d_1$ are both odd, then Equation (8) is equivalent to the congruence

$$t_1 c_1^2 \equiv -d_1 \mod 2 f_1, \quad c_1 \equiv c \mod 2 f_1.$$

The residue $-d_1/t_1$ mod $2 f_1$ is invertible and it is always 1 modulo 2. Therefore the number of solutions modulo $2 f_1$ is equal to $2^\delta(f_1)$ and they are all different modulo $f_1$. We put

$$c = c_1 + (x + y w_-(2 f_1) 2^{\delta_z(w)-1}) 2 f_1$$

taking $x$ mod $w_-(2 f_1)$ and $y$ mod $w_-(2 f_1) 2^{\delta_z(w)-1}$, where $2^{\delta_z(w)}$ is the 2-factor of $w$ for $w$ even and is 2 if $w$ is odd (so the factor $2^{\delta_z(w)-1}$ only appears if $w$ is even). For even or odd $w$ we obtain the same formula for the number of solutions $c$. This proves (ii).

(iii) Consider the case when $g_1$ and $f_1$ are both odd, and $d_1$ is even. Equation (8) is equivalent to the congruence (11) and $c_1$ is always even, i.e., $c_1 = 2 c_2$ and

$$c_2^2 \equiv -(d_1/2)/(2 t_1) \mod f_1$$

and $c_2$ is considered modulo $f_1$. In particular $w$ must be odd since otherwise $2|c, w)$. For odd $w$ we choose

$$c = 2 c_2 + (x + w_-(f_1) y) 2 f_1$$

with $x$ taken mod $w_-(f_1)$ and $y$ taken $w_-(f_1)$, and this completes the proof of (iii).
(iv) Fix a representative of the $O(L_{2t})$-orbit of $h_d$ of the form
\[ h_d = fe_1 + fbe_2 + cl_t \in U \oplus \langle -2t \rangle \] (12)
where $e_1$ and $e_2$ form a usual basis of the hyperbolic plane $U$ ($e_1^2 = e_2^2 = 0$ and $e_1 \cdot e_2 = 1$). The orthogonal complement of $h_d$ in $U \oplus \langle -2t \rangle$ is a lattice $L_B$ of rank 2
\[ L_B = (h_d)_{U \oplus \langle -2t \rangle}^\perp = \langle e_1 - be_2, c^2t e_2 + lt \rangle. \] (13)
with the quadratic form $B$ as in (iv). Both vectors are orthogonal to $h_d$: they form a basis because using them one can reduce to zero the coordinates at $e_1$ and at $l_t$. In the notation above we obtain
\[ B = g_1 \begin{pmatrix} -2b/g_1 & cwt_1 \\ cwt_1 & -w^2 f_1 t_1 \end{pmatrix}. \]
We have $(cwt_1, w^2 f_1 t_1) = wt_1(c, w f_1) = wt_1$. The greatest common divisor of the elements of $B$ is equal to $g_1(2b/g_1, w)$ because $2b/g_1$ and $t_1$ are coprime.

**Corollary 3.7** Let us assume that $w = 1$. If there exists a primitive vector $h_d \in L_{2t}$ such that $h_d^2 = 2d$ and $\text{div}(h_d) = f$, then all such vectors belong to the same $O(L_{2t})$-orbit.

**Proof.** The natural projection $O(L_{2t}) \to O(D(L_{2t}))$ is surjective (see [Nik]). Furthermore (see [GH])
\[ O(D(L_{2t})) \cong \{ x \mod 2t \mid x^2 \equiv 1 \mod 4t \}. \]
Therefore for $w = 1$ all solutions $c \mod f$ of the congruences (9) and (10) are equivalent modulo the action of this abelian 2-group. \qed

**Example 3.8** Let $f = 1$. From the Proposition 3.6 it follows that for any $t$ and $d$ there is only one $O(L_{2t})$-orbit of primitive vectors $h_d$ with $\text{div}(h_d) = 1$. Moreover $c = 0$ and so
\[ (h_d)^{t}_{L_{2t}} \cong L_{2t, 2d} = 2U \oplus 2E_8(-1) \oplus \langle -2t \rangle \oplus \langle -2d \rangle. \] (14)

**Definition 3.9** We call a polarisation determined by a primitive vector $h_d$ **split** if $\text{div}(h_d) = 1$ and **non-split** otherwise.

The name comes from the fact that $\text{div}(h_d) = 1$ is the only case when the matrix $B$ is diagonal because $c$ can be zero and coprime to $f$ only if $f = 1$. The split case will be the main subject of much of the rest of this paper.
Example 3.10 Let \( f = 2 \). In this case \( c \) is odd, so we may take \( c = 1 \). A constant \( b \) and a vector \( h_d \) exist if and only if \( d + t \equiv 0 \mod 4 \). Moreover the \( \tilde{O}(L_{2t}) \)-orbit of \( h_d \) is unique because \( D(L_{2t}) \) is cyclic and thus contains only one element of order 2.

If \( f > 2 \), then Proposition 3.6 shows that the number of orbits is zero or strictly greater than one. Thus the cases \( f = 1 \) and \( f = 2 \) are special in that they are the only cases where the degree determines the polarisation uniquely.

Example 3.11 Let \( d \) and \( t \) be coprime. Examples 3.8 and 3.10 give us the full classification of possible \( h_d \in L_{2t} \) (in particular if \( t = 1 \) or \( d = 1 \)), since if \( (t,d) = 1 \) then \( f = \text{div}(h_d) = 1 \) or 2.

In the next proposition we show that if \( w = 1 \), then the groups \( \tilde{O}(L_{2t}, h_d) \) and \( O(L_{2t}, h_d) \) have rather clear structure.

Proposition 3.12 Let \( h_d \in L_{2t} \) be a primitive vector such that \( h_d^2 = 2d \) and \( \text{div}(h_d) = f \). Assume that \( w = 1 \), i.e. \( f \) and \( (2t/f, 2d) \) are coprime. Then

(i) \( \tilde{O}(L_{2t}, h_d) \cong \tilde{O}((h_d)^\perp_{L_{2t}}) \).

(ii) The factor group \( O(L_{2t}, h_d)/\tilde{O}(L_{2t}, h_d) \) is an abelian 2-group, which is of order \( 2^{\rho(2t/f)} \) if \( f \) is odd. If \( f \) is even the order is equal to \( 2^{\rho(2t/f)} + \delta \), where

\[
\delta = \begin{cases}
0 & \text{if } (2t/f) \equiv 1 \mod 2 \text{ or } (2t/f) \equiv 4 \mod 8, \\
-1 & \text{if } (2t/f) \equiv 2 \mod 4, \\
1 & \text{if } (2t/f) \equiv 0 \mod 8.
\end{cases}
\]

Proof. We may take \( h_d \) in the form (12). We can fix a basis \( k_1, k_2 \) of \( L^\vee_B \) given by

\[
k_1 = \frac{f}{2d} h_d - e_2 = \frac{f}{2d} (fe_1 + bfe_2 + c lt) - e_2, \\
k_2 = \frac{c}{2d} h_d + \frac{1}{2t} l_t = \frac{f}{2d} (ce_1 + cbe_2 + \frac{b}{l} t_l).
\]

Up to sign, this is dual to the basis fixed in (13). We put

\[
k_3 = fk_2 - ck_1 = ce_2 + \frac{f}{2t} l_t.
\]

If \( v \in L^\vee \) we shall denote by \( \bar{v} \) the corresponding element in the discriminant group \( D(L) = L^\vee/L \). We note that the orders of \( \bar{k}_1 \) and of \( \bar{k}_3 \) in \( D(L_B) = D((h_d)^\perp_{L_{2t}}) \) (see (13)) are equal to \( 2d \) and \( 2t/f \) respectively. Moreover \( \bar{k}_1 \cdot \bar{k}_3 = 0 \). Let us calculate the order of the intersection of the subgroups generated by
$\bar{k}_1$ and $\bar{k}_3$ in $D(L_B)$. If $n\bar{k}_1 \in \langle \bar{k}_3 \rangle$ then $n = g_1d_1n_1$ because $m\bar{k}_3$ does not contain the $e_1$-component. Therefore $n\bar{k}_1 \equiv (\frac{n_1c}{w}l_1 + xe_2) \mod L_B$ where $x \in \mathbb{Z}$ (see [13]), and $|\langle \bar{k}_1 \rangle \cap \langle \bar{k}_3 \rangle | = w$. It follows that $\bar{k}_1$ and $\bar{k}_3$ form a basis of $D(L_B)$ if $w = 1$.

As in the beginning of the section we consider the following series of lattices

$$\langle h_d \rangle \oplus h_d^1 < L_d < h_d^{1} \oplus \langle h_d \rangle^\vee,$$

where $h_d^\vee = \frac{1}{2w}h_d$ and $h_d^1 = (h_d)_{L_d} \cong 2U \oplus 2E_{8}(-1) \oplus L_B$. The subgroup $H = L_d/(\langle h_d \rangle \oplus h_d^1)) < D(h_d) \oplus D(L_B)$ has order $\frac{2d}{f}$. It is generated by the element $\bar{k}_1 - fh_d/2d$. Therefore the projection

$$p(H) = p_{h_d^1}(H) = (\bar{k}_1)$$

is the subgroup generated by $\bar{k}_1$. It follows if $w = 1$ the discriminant group is

$$D(h_d^1) = \langle \bar{k}_1 \rangle \oplus \langle \bar{k}_3 \rangle = p(H) \oplus \langle \bar{k}_3 \rangle.$$

According to Lemma [3.2]

$$O(L_{2t}, h_d) \cong \{ \gamma \in O(h_d^1) \mid \bar{\gamma}|_{p(H)} = id \}.$$

Let us consider an element $\gamma \in O(h_d^1)$ satisfying $\bar{\gamma}|_{p(H)} = id$ as an element of $O(L_{2t}, h_d)$ (i.e., we put $\gamma(h_d) = h_d$). According to the decomposition above $\gamma \in \tilde{O}(L_{2t}, h_d)$ if and only if $\bar{\gamma}(\bar{k}_3) = \bar{k}_3$. Therefore $\tilde{O}(L_{2t}, h_d) \cong O(h_d^1)$.

We note that the natural projection $O(h_d^1) \rightarrow O(D(L_B))$ is surjective (see [Nik]). Therefore according to Lemma [3.2]

$$O(L_{2t}, h_d)/\tilde{O}(L_{2t}, h_d) \cong \{ \gamma \in O(h_d^1) \mid \bar{\gamma}|_{p(H)} = id \}/\tilde{O}(h_d^1) \cong O(\langle \bar{k}_3 \rangle),$$

where $\langle \bar{k}_3 \rangle = \{ nk_3 \mid n \mod \frac{2t}{f} \}$ and $\bar{k}_3 \equiv -\frac{f^2}{2t} \mod 2$. Therefore

$$O(\langle \bar{k}_3 \rangle) \cong \{ x \mod \frac{2t}{f} \mid x^2 \bar{k}_3 \equiv \bar{k}_3^2 \mod 2 \} = \{ x \mod \frac{2t}{f} \mid x^2 f \equiv f \mod 2\frac{2t}{f} \}.$$

We supposed that $w = 1$. Therefore $f = f_1$ and $g = g_1$ are coprime. We have $\frac{2t}{f} = g_1t_1$ with $(f_1, t_1) = 1$ (see Proposition [3.6]). It follows that the group $O(\langle \bar{k}_3 \rangle)$ is isomorphic to the group

$$\{ x \mod \frac{2t}{f} \mid x^2 \equiv 1 \mod 2^\varepsilon(f)\frac{2t}{f},$$

where $\varepsilon(f) = 1$ if $f$ is odd (in this case $\frac{2t}{f}$ is even) and $\varepsilon(f) = 0$ is $f$ is even. The last group is well-known (compare with [GH]).

**Corollary 3.13** We have that $O(L_{2t}, h_d) \cong \tilde{O}(L_{2t}, h_d)$ in the following three cases: $f$ is odd and $f = t$; or $f = 2t$; or $f = t$ and $2d/f$ is odd.
Proof. If \( f = t \) or \( f = 2t \), then \( g = (\frac{2t}{T}, \frac{2d}{T}) = 1 \) or 2. If \( g = 1 \), then \( w = 1 \). If \( g = 2 \) then \( w = (f,g) = 1 \) for odd \( f \) and for even \( f \) such that \((2d)/f\) is odd. In all these case the index \([O(L_{2t},h_d) : \tilde{O}(L_{2t},h_d)] = 1\) according Proposition 3.12.

Remark 3.14 The condition \( w = 1 \), i.e., that \( f \) and \((\frac{2t}{T}, \frac{2d}{T})\) are coprime, is valid for any \( f \) if \((2t,2d)\) is square free. In particular this condition is true for any vector \( h_d \) if \( 2t \) is square free.

Remark 3.15 The finite group \( O(D((hd)_{L_{2t}}^1)) \) is cyclic for any \( h_d \) with \( \text{div}(h_d) = f \) if \( g_1 = (\frac{2t}{T}, \frac{2d}{T}) = 1 \). If \( g_1 > 1 \) the discriminant group is not cyclic, but it is the orthogonal sum of two cyclic groups if \( w = 1 \). Proposition 3.12 shows that we can consider this rather general case as a regular one.

Since the classification of polarisation types in this section depends only on the discriminant group it immediately gives an identical classification for polarisations of deformations of generalised Kummer varieties.

4 Modular forms and root systems

For the rest of the paper we restrict to a special class of symplectic 4-folds. We consider the case of deformation K3\(^{[2]}\) manifolds with polarisation of degree \( 2d \) of split type, as in Example 3.8 above. We denote an irreducible component of the corresponding moduli space by \( M_{2d}^{[2], \text{split}} \). (We do not know whether there is only one irreducible component: see Question 2.6.)

According to Theorem 2.3 we have a dominant map

\[ M_{2d}^{[2], \text{split}} \to \tilde{O}(L_2,h_d) \backslash \Omega_{h_d}. \]

In this case, where \( t = 1 \), we have

\[ \tilde{O}(L_{2,2d}) = \tilde{O}(L_2,h_d) = O(L_2,h_d) \]

by Proposition 3.12(i) and Corollary 3.13 where \( L_{2,2d} \) is as defined in Equation (14). In particular the vertical map in Theorem 2.3 is of degree 1, and an affirmative answer to Question 2.6 would imply that global Torelli holds for deformation K3\(^{[2]}\) manifolds with polarisation of split type.

It is more convenient to express this quotient in terms of the symmetric domain \( D(L_{2,2d}) \) defined in Equation (1) above. Recall that \( \tilde{O}^+(L_{2,2d}) \) is the index 2 subgroup of \( \tilde{O}(L_{2,2d}) \) that preserves \( D(L_{2,2d}) \). Then

\[ \tilde{O}(L_2,h_d) \backslash \Omega_{h_d} = \tilde{O}^+(L_{2,2d}) \backslash D(L_{2,2d}). \]

In the rest of this paper we study the Kodaira dimension of the locally symmetric variety \( \tilde{O}^+(L_{2,2d}) \backslash D(L_{2,2d}) \) and of the moduli space \( M_{2d}^{[2], \text{split}} \).
Theorem 4.1 The variety $M_{2d}^{[2], \text{split}}$ is of general type if $d \geq 12$. Moreover its Kodaira dimension is non-negative if $d = 9$ and $d = 11$.

In the case $d = 11$ the split and non-split cases behave very differently. Debarre and Voisin [DV] give a geometric construction of a 20-dimensional family of irreducible symplectic manifolds with non-split polarisation with $d = 11$, and from their construction it follows immediately that the moduli space is unirational.

Let $L$ be an even integral lattice of signature $(2, n)$ with $n \geq 3$. A modular form of weight $k$ and character $\chi: \Gamma \to \mathbb{C}^*$ for a subgroup $\Gamma < O^+(L)$ of finite index is a holomorphic function $F: D_L^* \to \mathbb{C}$ on the affine cone $D_L^*$ over $D_L$ such that

$$F(tZ) = t^{-k}F(Z) \quad \forall t \in \mathbb{C}^* \quad \text{and} \quad F(gZ) = \chi(g)F(Z) \quad \forall g \in \Gamma.$$ 

A modular form is a cusp form if it vanishes at every cusp. For applications, we require the order of vanishing to be at least 1 (both here and in [GHS1], although it is not stated explicitly there). In general this is a slightly stronger requirement because the order of vanishing might be a rational number less than 1. However, it is easy to check that for trivial character and character det, which are the cases used here and in [GHS1], the vanishing order at any cusp is an integer.

We denote the linear spaces of modular and cusp forms of weight $k$ and character $\chi$ for $\Gamma$ by $M_k(\Gamma, \chi)$ and $S_k(\Gamma, \chi)$ respectively.

The next theorem follows from the results obtained in [GHS1].

**Theorem 4.2** Suppose there exists a non-zero cusp form $F_a$ of some weight $a < 20$ and character $\text{det}$ with respect to the modular group $O^+(L_{2,2d})$. Then the modular variety $M_{2d}^{[2], \text{split}}$ is of general type.

If there exists a non-zero cusp form $F_{20}$ of weight 20 and character $\text{det}$ then $M_{2d}^{[2], \text{split}}$ has non-negative Kodaira dimension.

**Proof.** $M_{2d}^{[2], \text{split}}$ is a quasi-projective variety of dimension 20. It has a toroidal compactification having only canonical singularities, by [GHS1, Theorem 2]. By [GHS1, Theorem 1.1], the variety $M_{2d}^{[2], \text{split}}$ is of general type if there exists a non-zero cusp form $F_a \in S_a(\tilde{O}^+(L_{2,2d}))$ of weight $a < 20$ that vanishes along the ramification divisor of the projection

$$\pi: D(L_{2,2d}) \longrightarrow \tilde{O}^+(L_{2,2d})\backslash D(L_{2,2d}).$$

We note that according to [GHS1, Corollary 2.13] the ramification divisor is determined by the elements $\sigma \in O(L_{2,2d})$ such that $\sigma$ or $-\sigma$ is a reflection with respect to a vector $r \in L_{2,2d}$. We classified those reflections using the results of [GHS1, §3].
Let \( F_a \in S_a(\hat{\Omega}^+(L_{2,2d}), \det) \) be of weight \( a < 20 \) and suppose that \( \sigma \in \hat{\Omega}(L_{2,2d}) \) defines a component of the ramification divisor. Then

\[
F_a(\pm \sigma(Z)) = \det(\pm \sigma) \cdot F_a(Z) = -F_a(Z)
\]

because \( \det(-\sigma) = (-1)^{20} \det(\sigma) = -1 \). Therefore the cusp form \( F_a \) with character \( \det \) automatically vanishes on the ramification divisor.

If \( a = 20 \) and \( F_{20} \) vanishes along the ramification divisor of \( \pi \) then \( F_{20} \) determines a section of the canonical bundle by a well-known result of Freitag [Fr] Hilfssatz 2.1, Kap. III].

One can estimate the obstructions to continuing of the pluricanonical forms across the ramification divisor using the exact formula for Mumford–Hirzebruch volume of the corresponding orthogonal groups (see [GHS2]). But this approach only gives good results for locally symmetric varieties of orthogonal type if the dimension is quite large: at least 33 in the cases considered in [GHS3].

If the dimension of the modular variety is smaller than 26 we can use the quasi pull-back (see Equation (15) below) of the Borcherds modular form \( \Phi_{12} \) to construct cusp forms of small weight. The Borcherds form is a modular form of weight 12 for \( O^+(II_{2,26}) \), where \( II_{2,26} \) is the unimodular lattice \( 2U \oplus 3E_8(-1) \).

\( \Phi_{12}(Z) = 0 \) if and only if there exists \( r \in II_{2,26} \) with \( r^2 = -2 \) such that \( (r, Z) = 0 \). Moreover, the multiplicity of the rational quadratic divisor in the divisor of zeros of \( \Phi_{12} \) is 1 (see [Bo]). This form generates very important functions on the moduli spaces of polarised K3 surfaces (see [BKPS], [Ko] and [GHS1]). In the context of the moduli space of symplectic manifolds we can use the following specialisation of the quasi pull-back.

The Weyl group of \( E_8 \) acts transitively on the roots of \( E_8 \). If \( v \) is a root of \( E_8(-1) \) then \( v E_8(-1) \cong E_7(-1) \). Let \( l \in E_7(-1) \) satisfy \( l^2 = -2d \). The choice of \( v \) and \( l \) determines an embedding of \( L_{2,2d} \) into \( II_{2,26} \). The embedding of the lattice also gives us an embedding of the domain \( D(L_{2,2d}) \subset \mathbb{P}(L_{2,2d} \otimes \mathbb{C}) \) into \( D(II_{2,26}) \subset \mathbb{P}(II_{2,26} \otimes \mathbb{C}) \).

We put \( R_l = \{ r \in E_7(-1) \mid r^2 = -2, \ (r, l) = 0 \} \), and \( N_l = \# R_l \). (It is clear that \( N_l \) is even.) We note that \( R_l \) is the set of roots orthogonal to the sublattice \( \langle v \rangle \oplus \langle l \rangle \) in \( E_8(-1) \). Then the quasi pull-back of \( \Phi_{12} \) is given by the following formula (see [BKPS]):

\[
F_l = \frac{\Phi_{12}(Z)}{\prod_{\{ \pm r \} \in R_l} (Z, r)} \bigg|_{D(L_{2,2d})} \in M_{12 + \frac{N_l}{2}}(\hat{\Omega}^+(L_{2,2d}), \det). \tag{15}
\]

It is a non-trivial modular form of weight \( 12 + \frac{N_l}{2} \). By [GHS1] Theorem 6.2 it is a cusp form if \( N_l \) is non empty. In [GHS1] we proved this for \( l \in E_8(-1) \). But in the proof we used only the fact that any isotropic subgroup of the
The lattice \( E \) used in the proof of [GHS1, Theorem 7.1]. We first need some properties of lattices of \( W \).

Sufficient conditions are given in Theorem 4.5 below. We apply the method used in the proof of [GHS1 Theorem 7.1]. We first need some properties of the lattice \( E_7 \).

**Lemma 4.3** The Weyl group \( W(E_7) \) acts transitively on the sets of sublattices of \( E_7 \) of types \( A_1 \oplus A_1 \) or \( A_2 \).

**Proof.** \( W(E_7) \) acts transitively on the roots. Moreover \( (A_1)_{E_7}^{1/2} \cong D_6 \) and \( W(D_6) \) acts transitively on its roots. This proves the \( A_1 \oplus A_1 \) case.

Let \( A_2^{(1)} \), \( A_2^{(2)} \) be two different copies of \( A_2 \) in \( E_7 \). Without loss of generality we can assume that they have a common root \( a \), i.e. \( A_2^{(1)} = A_2^{(2)} = A_2(a, c) = Z a + Z c \) and \( A_2^{(2)} = A_2(a, d) \), where \( a \cdot c = a \cdot d = -1 \). Any \( A_2 \)-lattice contains six roots

\[
R(A_2(a, c)) = \{ \pm a, \pm c, \pm (a + c) \}
\]

and it is generated by any pair of linearly independent roots. If \( c \cdot d = -1 \) then \( (a + d) \cdot c = -2 \), \( c = -(a + d) \) and \( A_2(a, c) = A_2(a, d) \). Therefore \( c \cdot d = 0 \) or 1. (We recall that for any two non-collinear roots \( u \) and \( v \) one has \( |u \cdot v| \leq 1 \).)

If \( c \cdot d = 1 \) then \( (c - d)^2 = 2 \) and \( (c - d) \cdot a = 0 \). The reflection \( \sigma_{c-d} \) with respect to the root \( (c - d) \) transforms \( A_2^{(1)} \) into \( A_2^{(2)} \):

\[
\sigma_{c-d}(c) = c - (c \cdot (c - d))(c - d) = d, \quad \sigma_{c-d}(a) = a.
\]

If \( c \cdot d = 0 \) then \( A_2(a, c) + A_2(a, d) \) is a root lattice of type \( A_3 \) with 12 roots:

\[
R(A_3(a, c, d)) = \{ a, c, d, a + c, a + d, a + c + d \}.
\]

The roots \( \pm (a + c + d) \) are the only roots in \( A_3(a, c, d) \) orthogonal to \( a \). We have \( \sigma_{a+c+d}(c) = -(a + d) \). To find a reflection \( \sigma \) such that \( \sigma(a) = a \) and \( \sigma(-(a+d)) = d \) we have to go outside of \( A_3 = A_2(a, c) + A_2(a, d) \). We recall that \( E_7 \) contains 126 roots (see [Bou]):

\[
R(E_7) = \{ \pm (e_7 - e_8) \} \cup \{ \pm e_i \pm e_j \mid 1 \leq i < j \leq 6 \}
\]

\[
\cup \{ \pm \frac{1}{2}(e_7 - e_8) + \frac{1}{2} \sum_{i=1}^{6} (-1)^{\nu(i)} e_i \mid \sum_{i=1}^{6} \nu(i) \text{ is even} \}
\]

where \( e_i \) form the usual Euclidian basis in \( \mathbb{Z}^8 \). Without loss of generality we can assume that \( a = e_7 - e_8 \). Since \( a \cdot d = -1 \), we see that

\[
d = -\frac{1}{2}(e_7 - e_8) + \frac{1}{2} \sum_{i=1}^{6} (-1)^{\nu(i)} e_i.
\]
We put \( r_j = (-1)^{j(j-1)/2} e_j + (-1)^{(j+1)(j+2)/2} e_{j+1} \) for \( j = 1, 3 \) and 5. We obtain
\[
\sigma_r \circ \sigma_r \circ \sigma_r(d) = d - r_1 - r_3 - r_5 = -(a + d).
\]
\(\square\)

**Corollary 4.4** We have

(i) The Weyl group \( W(E_8) \) acts transitively on all its sublattices of types \( 3A_1 \) and \( A_1 \oplus A_2 \) in \( E_8 \).

(ii) The class number of the lattices \( A_5 \) and \( A_1 \oplus D_4 \) is equal to one.

(iii) The sublattices \( 4A_1 \) in \( E_8 \) form two orbits with respect to \( W(E_8) \).

*Proof.* (i) follows from the fact that \( (A_1)_{E_8} \cong E_7 \). To prove (ii) we note that \( A_1 \oplus D_4 \) is a maximal lattice because its discriminant group does not contain any isotropic vectors. (The square of any element in \( D_4^\vee / D_4 \) is equal to \( 1/2 \) modulo 2.) Furthermore
\[
(A_1)_{E_7} \cong D_6, \quad (A_1)_{D_6} \cong A_1 \oplus D_4, \quad (A_2)_{E_7} \cong A_5.
\]

(16)

To see these one has to use the extended Dynkin diagram of the corresponding root lattice and to take into account the maximality of \( D_6, A_5 \) and \( A_1 \oplus D_4 \). The discriminant quadratic form is the invariant of the genus of an even quadratic lattice. Therefore if \( M \) is a lattice in the genus of \( A_1 \oplus D_4 \) then we can consider \( M \oplus 2A_1 \) as a sublattice of \( E_7 \). All such \( M \) are isomorphic according to the lemma. The same argument works for \( A_5 \).

To prove (iii) we remark that \( (3A_1)_{E_8} \cong A_1 \oplus D_4 \). The last lattice contains two orbits of roots. \(\square\)

**Theorem 4.5** There exists a vector \( l \) in \( E_7 \) of length \( 2d \) orthogonal to at least 2 and at most 14 roots if
\[
30N_{A_1 \oplus D_4}(2d) + 16N_{A_5}(2d) < 5N_{D_6}(2d)
\]

or to at least 2 and at most 16 roots if
\[
30N_{A_1 \oplus D_4}(2d) + 16N_{A_5}(2d) < 6N_{D_6}(2d),
\]

where \( N_L(2d) \) denotes the number of representations of \( 2d \) by the lattice \( L \).

*Proof.* Suppose that any vector \( l \in E_7 \) of length \( 2d \) is orthogonal to at least 16 roots if it is orthogonal to any. Let us fix a root \( a \) in \( E_7 \) orthogonal to \( l \). Therefore \( l \in a_{E_7} = D_6^{(a)} \). The others roots orthogonal to \( l \) are some roots in \( D_6^{(a)} \) (60 roots) or roots in \( R(E_7) \setminus R(D_6^{(a)}) \) (66 roots). The last 66 roots form a bouquet \( Q_6(16A_2) \) of 16 copies \( A_2(a) \) of \( A_2 \) centred in \( \pm a \). If \( l \) is
orthogonal to any root from $A_2(a)$ different from $a$, then $l$ is orthogonal to the whole lattice $A_2(a)$ and $l \in (A_2)_{E_7} \cong A_5$. If $l$ is orthogonal to a root in $D_6^{(a)}$ then $l \in (2A_1)_{E_7} \cong A_1 \oplus D_4$. Therefore we have

$$l \in \bigcup_{i=1}^{30} (A_1 \oplus D_4)^{(i)} \cup \bigcup_{j=1}^{16} A_5^{(j)}. \tag{19}$$

Denote by $n(l)$ the number of components in (19) containing the vector $l$. We have calculated this vector exactly $n(l)$ times in the sum $30N_{A_1 \oplus D_4}(2d) + 16N_{A_5}(2d)$.

We need to estimate $n(l)$. We shall consider several cases.

1. Let $l \cdot c \neq 0$ for any $c \in Q_a(16A_2) \setminus \{\pm a\}$. Then $l$ is orthogonal to at least 7 copies of $A_1$ in $D_6^{(a)}$ and $n(l) \geq 7$.

Now we suppose that there exist $c \in Q_a(16A_2) \setminus \{\pm a\}$ such that $l \cdot c = 0$. Then $l$ is orthogonal to $A_2(a,c)$ which is one of the 16 subsystems of the bouquet $Q_a$.

2. If $l$ is orthogonal to only one copy of $A_2$ in $Q_a$, $A_2^{(i)}$ (6 roots) then $l$ is orthogonal to at least 5 copies of $A_1$ in $D_6^{(a)}$. Thus $n(l) \geq 6$.

3. If $l$ is orthogonal to exactly two copies of $A_2$ in $Q_a$, $A_2^{(i)}$ and $A_2^{(j)}$, then $l$ is orthogonal to $A_3 = A_2^{(i)} + A_2^{(j)}$ having 12 roots. Thus $l$ is orthogonal to another $2A_1$ in $D_6^{(a)}$. But $A_3$ contains one more copy $A_1$ from $D_6^{(a)}$ orthogonal to $a$ (see the proof of Lemma 4.3). Therefore $n(l) \geq 5$.

4. If $l$ is orthogonal to three or more $A_2^{(i)}$ then their sum contains at least three $A_1 < D_6^{(a)}$ and $n(l) \geq 6$.

Therefore we have proved that if any $l \in E_7$ with $l^2 = 2d$ is orthogonal to at least 16 roots then $n(l) \geq 5$ and

$$30N_{A_1 \oplus D_4}(2d) + 16N_{A_5}(2d) \geq 5N_{D_6}(2d).$$

If we replace 16 roots by 18 roots in the last condition then we obtain the second inequality of Theorem 4.5

$$30N_{A_1 \oplus D_4}(2d) + 16N_{A_5}(2d) \geq 6N_{D_6}(2d).$$

\[\square\]

5 Representations by quadratic forms of odd rank

To estimate the values of $d$ for which the inequality of Theorem 4.5 is true we need exact formulae for the numbers $N_{A_1 \oplus D_4}(2d)$ and $N_{A_5}(2d)$.
Let $A$ be a symmetric even integral positive definite $m \times m$ matrix of determinant $\det A = |A|$, and

$$S(X) = \frac{1}{2} A[X] = \frac{1}{2} X A X$$

be the corresponding quadratic form taking integral values on $\mathbb{Z}^m$. The genus $\text{gen } S$ of $S$ contains a finite number of classes $S_i$. The integral orthogonal group $O(S_i)$ is finite of order $|O(S_i)|$. One defines the mass of the genus by

$$\text{mass}(S) = \sum_{S_i \in \text{gen } S} |O(S_i)|^{-1}$$

and the weight of the class $S_i$ in the genus of $S$ by

$$w(S_i) = |O(S_i)|^{-1} / \text{mass}(S).$$

Siegel’s main theorem on quadratic forms (see [Si]) tells us that the number of representations of $t$ by the genus of $S$, defined by

$$r(t, \text{gen } S) = \sum_{S_i \in \text{gen } S} w(S_i) r(t, S_i)$$

where $r(t, S_i)$ is the number of the representation of $t$ by the quadratic form $S_i$, can be written in terms of the local densities $\alpha_p(t, S)$

$$r(t, \text{gen } S) = \varepsilon_m \prod_{p \leq \infty} \alpha_p(t, S),$$

where $\varepsilon_m = 1$ for all $m \geq 2$ except $\varepsilon_2 = 1/2$. The local densities (or the local measures of the representations of $t$ by $S$) are defined as follows

$$\alpha_p(t, S) = \lim_{a \to \infty} p^{-a(m-1)} \# \{ X \in (\mathbb{Z}/p^a \mathbb{Z})^m \mid S(X) \equiv t \mod p^a \}$$

if $p$ is a finite prime and

$$\alpha_{\infty}(t, S) = \lim_{V \to t} \frac{\text{vol } S^{-1}(V)}{\text{vol } V} = (2\pi)^{m/2} \Gamma(\frac{m}{2})^{-1} t^{\frac{m}{2}} - 1 |A|^{-\frac{1}{2}},$$

where $|A| = \det(A)$, $V$ is a real neighbourhood of $t$ and $\text{vol}$ is the usual Euclidian volume in $\mathbb{R}$ or $\mathbb{R}^m$ (see [Si] Hilfssatz 26 and (71)).

If the genus of $S$ contains only one class then the Siegel formula gives us an exact formula for the number $r(t, S)$ of representations of $t$ by $S$. In his first paper [Si] on the analytic theory of quadratic forms Siegel found exact formulae for the local densities if the prime $p$ is not a divisor of the determinant of $A$. If the rank $m \geq 4$ is even we have the following formula (see [Iw] (11.74))

$$r(t, \text{gen } S) = a_{\infty}(t, S) L(\frac{m}{2}, \chi_4D)^{-1} \left( \sum_{a \mid t} \chi_4D(a) a^{-\frac{m}{2}} \right) \cdot \prod_{p \mid 2D} \alpha_p(t, S) \quad (20)$$
where \( D = (-1)^{m/2} |A| \) is the discriminant of \( A \) and \( \chi_{4D}(a) = \left( \frac{4D}{a} \right) \) is the quadratic character.

Usually the exact computation of the local densities for odd rank \( m \) is said to be more complicated: see for example the introduction to [Sh]. Here we give a well-organised formula for \( r(t, \text{gen} S) \) for odd rank \( m \). For this purpose we use the Zagier \( L \)-function \( L(s, \Delta) \) and the H. Cohen numbers \( H(n, \Delta) \) (see [C] and [Za]). In these terms, surprisingly, the exact formula for odd rank is simpler than the formula (20) for even rank.

If \( \Delta \equiv 0, 1 \mod 4 \) then \( \Delta = Df^2 \), where \( D \) is the discriminant of the quadratic field \( \mathbb{Q}(\sqrt{\Delta}) \). By definition (see [Za, (7) and Proposition 3]) one has

\[
L(s, \Delta) = \frac{\zeta(2s)}{\zeta(s)} \sum_{n=1}^{\infty} b_n(\Delta) n^{-s},
\]

where \( b_n(\Delta) = \# \{ x \mod 2n \mid x^2 \equiv \Delta \mod 4n \} \),

\[
L(s, \Delta) = L(s, \chi_D) \sum_{a | f} \mu(a) \left( \frac{D}{a} \right) a^{-s} \sigma_{1-2s}(\frac{f}{a}),
\]

where \( \sigma_s(t) = \sum_{d | t} d^s \) and \( \mu(a) \) is the Möbius function. The main advantage of \( L(s, \Delta) \) is the fact that it satisfies a simple functional equation.

The function

\[
L^*(s, \Delta) = \begin{cases} 
\pi^{-\frac{s}{2}} \Gamma\left(\frac{s}{2}\right) \Delta^{\frac{s}{2}} L(s, \Delta) & \text{if } \Delta > 0 \\
\pi^{-\frac{s}{2}} \Gamma\left(\frac{s+1}{2}\right) |\Delta|^\frac{s}{2} L(s, \Delta) & \text{if } \Delta < 0
\end{cases}
\]

has a meromorphic continuation to the whole complex plane and satisfies the functional equation

\[
L^*(s, \Delta) = L^*(1-s, \Delta)
\]

(see [Za, Proposition 3]). Moreover \( L(s, \Delta) \) is entire except for a simple pole (of residue \( \frac{1}{2} \) if \( \Delta = 0 \) and 1 otherwise) if \( \Delta \) is a square. This function is very useful for calculation of Fourier coefficients of various Eisenstein series (see [C], [Za] and [GS-P]).

To formulate our reorganisation of the Siegel formula for odd rank \( m \) we introduce some notation. We write

\[
t = t_A t_1 t_2^2,
\]

where \( t_1 \) is square free, \( (t_1 t_2^2, |A|) = 1 \) and \( t_A \) divides some power of \( |A| \). We put

\[
D = \text{disc } \mathbb{Q} \left( \sqrt{(-1)^{m-2} 2t |A|} \right).
\]

We note that \( D > 0 \) if \( m \equiv 1 \mod 4 \) and \( D < 0 \) if \( m \equiv 3 \mod 4 \). The determinant of \( A \) is always even if \( m \) is odd and \( A \) is even integral.
Theorem 5.1 Let \( m = 2m_1 + 1 \) and \( S(X) = \frac{1}{2}A[X] \). Then we have

\[
\begin{align*}
\alpha_p(t, S) &= (1 - p^{-m}) \left( 1 + p^{2-m} + \cdots + p^{(2-m)\frac{m_1}{2}} \right) \\
\alpha_p(t, S) &= (1 - p^{-m}) \left( 1 + p^{2-m} + \cdots + p^{(2-m)\frac{m_1}{2}} + \frac{p^{(2-m)\frac{m_1}{2}}}{1 - \varepsilon_{A,t} (p)p^{\frac{1-m}{2}}} \right)
\end{align*}
\]

for \( l_p \equiv 1 \mod 2 \) and

\[
\begin{align*}
\alpha_p(t, S) &= (1 - p^{-m}) \left( 1 + p^{2-m} + \cdots + p^{(2-m)(\frac{m_1}{2})-1} + \frac{p^{(2-m)\frac{m_1}{2}}}{1 - \varepsilon_{A,t} (p)p^{\frac{1-m}{2}}} \right)
\end{align*}
\]

for \( l_p \equiv 0 \mod 2 \), where \( \varepsilon_{A,t} (p) = \left( \frac{-1}{2} \right)^{\frac{m_1}{2}} |A|^{2t_p} \). If \( l_p = 0 \) we take only the last summand in the second bracket (see [Si, Hilfssatz 12]).
numbers $Dt_2^2$ and $2t|A|$ differ by a square $f^2$ such that $f$ divides some power of $|A|$. Therefore if $p$ does not divide $|A|$ and $l_p$ is even then

$$\varepsilon_{A,t}(p) = \chi_D(p) = \left(\frac{D}{p}\right) \neq 0.$$  

If $l_p$ is odd then $p|D$ and $\chi_D(p) = 0$.

Let us reorganise the $p$-factors in the Siegel formulae for the local densities. We put

$$\alpha_p(t, S) = \left(\frac{1 - p^{1-m}}{1 - \chi_D(p)p^{\frac{1-m}{2}}}\right) p^{(2-m)\left\lfloor \frac{l_p}{2} \right\rfloor} \left(1 + \sum_{1 \leq j \leq l_p/2} p^{(m-2)j} \cdot \left(1 - \chi_D(p)p^{\frac{1-m}{2}}\right)\right).$$  

This formula is valid for both even and odd $l_p$. If $l_p = 1$ (i.e. if $p$ divides only $t_1$, not $t_2$) then $\alpha_p(t, S) = 1 - p^{1-m}$.

Taking the product over all divisors of $t_2$ we obtain the factor

$$t_2^{2-m} \sum_{d|t_2} d^{m-2} \prod_{p|d} \left(1 - \chi_D(p)p^{\frac{1-m}{2}}\right) = \sum_{a|t_2} \mu(a)\chi_D(a)a^{-\frac{1-m}{2}}\sigma_{2-m}\left(\frac{t_2}{a}\right).$$

Using the functional equation we can express $L(m_1, Dt_2^{2})$ in terms of $L(1 - m_1, Dt_2^{2}) = H(m_1, Dt_2^{2})$. Together with the formula for the Bernoulli numbers

$$(-1)^{m_1+1} \frac{B_{2m_1}}{2m_1} = \pi^{-\frac{1}{2}}2^{-2m_1}\Gamma(m_1)\Gamma(m_1 + \frac{1}{2})\zeta(2m_1)$$

it gives us the second formula [23]. We note that $(-1)^{[m_1/2]}H(m_1, Dt_2^{2})$ are positive rational numbers with bounded denominators. The denominators are 120 for $m_1 = 2$, 252 for $m_1 = 3$, 240 for $m_1 = 4$, etc. (see [C]).

The exact formulae for the local densities $\alpha_p(t, S), S(X) = \frac{1}{2}A[X]$, for all prime divisors of the determinant of $A$ including $p = 2$ were calculated in many papers. See for example Malyshev [Ma], who used a classical method of Gauss sums, and Yang [Ya], who calculated the local densities in terms of local Whittaker integrals. In the examples below we use the formulae of [Ya].

**Example 5.2** *The sum of five squares.*

Let $S_5(X) = x_1^2 + \cdots + x_5^2$. In this example we are finishing the calculation of Siegel (see [Si, §10]) who found $r(t, S_5)$ for odd $t$. According to Theorem 5.1 we have

$$r(t, S_5) = t^{3/2} \frac{120}{\pi^2} L(2, Dt_2^{2}) \frac{1 - \chi_D(2)2^{-2}}{1 - 2^{-4}} \alpha_2(t, S_5),$$

29
where \( t = 2^n t_1 t_2 \) with \( a = 2b \) or \( 2b + 1 \) as in Theorem 5.1. \( D = \text{disc } \mathbb{Q}(\sqrt{t}) \).

The formula for \( \alpha_2(t, S) \) (see [Ya, pp. 323–324]) is rather too long to give here. After some tedious transformations we obtain that

\[
\alpha_2(t, S_5) = 1 - \sum_{k=1}^{b} 2^{-3k+1} + (-1)^D 2^{-3b-2} - \chi_D(2) 2^{-3b-3},
\]

where \( \chi_D(2) = 0 \) if \( D \equiv 0 \mod 4 \) and \( \chi_D(2) = 1 \) or \(-1\) if \( D \equiv 1 \mod 8 \) or \( D \equiv 5 \mod 8 \) respectively. In terms of the Cohen numbers we have the numerical formula

\[
r(t, S_5) = \begin{cases} 
-40H(2, Dt_2^2) \cdot \frac{2^{2b+2} + 3}{7} & \text{if } D \equiv 0 \mod 4, \\
-120H(2, Dt_2^2) \cdot \left( \frac{5 \cdot 2^{3b+3} + 2}{7} - \chi_D(2) \right) & \text{if } D \equiv 1 \mod 4.
\end{cases}
\]

We note that \( Dt_2^2 \) is equal to \( t \) up to a power of 2.

Let \( L \) be an even integral quadratic lattice and \( q_L(x) \) and \( b_L(x, y) \) be the corresponding finite quadratic and bilinear forms on the discriminant group \( D(L) = L^\vee/L \). For \( q_L \) we have the local decomposition

\[
q_L = \bigoplus_p (q_L)_p = \bigoplus_p q_L \otimes \mathbb{Z}_p,
\]

where \( (q_L)_p \) is the finite quadratic form with values in \( \mathbb{Q}_p/\mathbb{Z}_p \) (\( p \neq 2 \)) or in \( \mathbb{Q}_2/2\mathbb{Z}_2 \) and \( (q_L)_p \) is the discriminant form on the \( p \)-component of the finite abelian group \( L^\vee/L \) with values in \( \mathbb{Q}(p)/\mathbb{Z} \cong \mathbb{Q}_p/\mathbb{Z}_p \) or in \( \mathbb{Q}(2)/2\mathbb{Z} \) (\( \mathbb{Q}(p) \) is the ring of fractions whose denominator is a power of \( p \)). A similar decomposition is valid for \( b_L \). We recall that any quadratic form over the \( p \)-adic integers \( \mathbb{Z}_p \) (\( p \neq 2 \)) is equivalent to a diagonal form. For \( p = 2 \) it can be represented as a sum of forms of types \( 2^n u x^2 \) \((u \in \mathbb{Z}_2^*/(\mathbb{Z}_2^*)^2)\), \( 2^n (2x_1x_2) \) and \( 2^n (x_1^2 + 2x_1x_2 + x_2^2) \).

**Example 5.3** The root lattice \( A_1 \oplus D_4 \).

The quadratic form \( S_{1,4} \) of this lattice is similar to the sum of five squares. More exactly

\[
S_{1,4} = x_1^2 + \frac{1}{2}(x_2^2 + x_3^2 + x_4^2 + x_5^2), \quad \text{where } x_2 + x_3 + x_4 + x_5 \text{ is even.}
\]

The determinant of \( A_1 \oplus D_4 \) is equal to 8. The discriminant form of \( D_4 \) is equal to the discriminant form of \( V(2) = 2(2x_1^2 + 2x_1x_2 + 2x_2^2) \). Using this we obtain that over \( \mathbb{Z}_2 \)

\[
\frac{1}{2}(A_1 \oplus D_4) \otimes \mathbb{Z}_2 \cong (2) \oplus \frac{1}{2} \left( \begin{array}{cc} 2 & 1 \\ 1 & 2 \end{array} \right) \oplus \left( \begin{array}{cc} 2 & 1 \\ 1 & 2 \end{array} \right)
\]

30
We use the notation of the previous example for \( t = 2^a t_1 t_2^2 \), \( a = 2b \) or \( 2b + 1 \). Again using [Ya] we obtain

\[
\alpha_2(t, S_{1,4}) = 1 - \sum_{k=1}^{b} 2^{-3k} + (-1)^D 2^{-3(b+1)} - \chi_D(2) 2^{-3b-4}.
\] (26)

The second formula (23) of Theorem 5.1 is

\[
\begin{align*}
    r(t, S_{1,4}) &= \begin{cases} 
        -8H(2, Dt_2^2) \cdot 2^{3b+3} \alpha_2(t, S_{1,4}), & \text{if } D \equiv 0 \mod 4, \\
        -120H(2, Dt_2^2) \cdot 2^{3b+4} \alpha_2(t, S_{1,4}), & \text{if } D \equiv 1 \mod 4.
    \end{cases}
\end{align*}
\]

The first formula (22) of Theorem 5.1 gives us an expression which we shall use later in our estimations of \( N_{A_5 \oplus D}(2d) \):

\[
\begin{align*}
    r(t, S_{1,4}) &= t^{3/2} \frac{32 \zeta(2) L(2, Dt_2^2)}{\zeta(4)} \frac{1 - \chi_D(2) 2^{-2}}{1 - 2^{-4}} \alpha_2(t, S_{1,4}). \\
    &= t^{3/2} \frac{\zeta(2) L(2, Dt_2^2)}{\zeta(4)} \frac{1 - \chi_D(2) 2^{-2}}{1 - 2^{-4}} \alpha_2(t, S_{1,4}).
\end{align*}
\] (27)

See (21) in order to understand the form of the factors.

**Example 5.4** The root lattice \( A_5 \).

Let \( D = \text{disc } Q(\sqrt{3}t) \) and \( t = 2^a 3^c t_1 t_2^2 \). According to Theorem 5.1

\[
\begin{align*}
    r(t, \frac{1}{2}A_5) &= t^{3/2} \frac{32 \zeta(2) L(2, Dt_2^2)}{\zeta(4)} \prod_{p=2,3} \frac{1 - \chi_D(p) 2^{-2}}{1 - p^{-4}} \alpha_p(t, \frac{1}{2}A_5).
\end{align*}
\]

The discriminant form of the lattice \( A_5 \) is the cyclic group of order 6 generated by the element \( \bar{v} \) such that \( \bar{v} \cdot \bar{v} \equiv \frac{5}{6} \mod 2\mathbb{Z} \). For the local part of the discriminant group we have

\[
\begin{align*}
    D(A_5)_3 &= \langle 2\bar{v} \rangle, & (2\bar{v})^2 &\equiv \frac{1}{3} \mod \mathbb{Z}_3, \\
    D(A_5)_2 &= \langle 3\bar{v} \rangle, & (3\bar{v})^2 &\equiv \frac{1}{2} \mod 2\mathbb{Z}_2.
\end{align*}
\]

It follows that

\[
A_5 \otimes \mathbb{Z}_3 \cong x_1^2 + x_2^2 + x_3^2 + 2x_4^2 + 3x_5^2
\]

and

\[
A_5 \otimes \mathbb{Z}_2 \cong 2x_1x_2 + 2x_3x_4 + 6x_5^2 \cong 2U \oplus \langle 6 \rangle.
\]

Put \( t' = 2^a t_1 t_2^2 \), so that \( t = 3^c t' \) and \( (3, t') = 1 \). The formula for \( \alpha_3 \) (see [Ya] p. 317) after some transformations can be written as follows

\[
\alpha_3(3^c t', \frac{1}{2}A_5) = 1 - \sum_{k=1}^{3(c+2)} (\frac{k}{3}) 3^{-k} + \left(\frac{t'}{3}\right) 3^{-\frac{3(c+2)}{2}},
\] (28)

31
where \(\left(\frac{c}{D}\right)\) is the Legendre symbol and we add the last term only if \(c\) is odd. For \(p = 2\), we put \(a = 2b\) or \(2b + 1\) and obtain

\[
\alpha_2(t, \frac{1}{2} A_5) = 1 + \sum_{k=1}^{b} 2^{-3k-1} - (-1)^D 2^{-3b-4} + \chi_D(2) 2^{-3b-5}.
\] (29)

In terms of the Cohen numbers we have

\[
r(2t, A_5) = \left(\frac{t_{A_5}}{D_{A_5}}\right)^{3/2} \frac{1}{\sqrt{3}} 2^5 \cdot 30(-H(2, Dt_2^2)) \prod_{p=2,3} \frac{1 - \chi_D(p)p^{-2}}{1 - p^{-4}} \alpha_p(t, \frac{1}{2} A_5),
\]

where \(t_{A_5} = 2^a 3^c\) and \(D_{A_5}\) are the products of the powers of 2 and 3 in \(t\) and \(D\).

**Proposition 5.5** The inequality

\[
30N_{A_1 \oplus D_4}(2m) + 16N_{A_5}(2m) < 5N_{D_6}(2m)
\]

is true for any \(m \geq 20\) and for \(m = 17\). The inequality

\[
30N_{A_1 \oplus D_4}(2m) + 16N_{A_5}(2m) < 6N_{D_6}(2m).
\]

is true if \(m \geq 12\).

**Proof.** First we estimate \(N_{D_6}(2m)\) from below. By definition

\[
D_6 = \{(x_i) \in \mathbb{Z}^6 \mid x_1 + \cdots + x_6 \in 2\mathbb{Z}\}.
\]

Therefore the number \(N_{D_6}(2m)\) is equal to the number of representation of \(2m\) by six squares. It is classically known (see [Iw] p. 187) and it can be easily proved using Eisenstein series or the Siegel main formula that

\[
N_{D_6}(2m) = 64\tilde{\sigma}_2(m, \chi_4) - 4\sigma_2(m, \chi_4)
\]

where \(\chi_4(m) = \left(\frac{-4}{m}\right)\) is the unique non-trivial Dirichlet character modulo 4 and for any Dirichlet character \(\chi\) we put

\[
\sigma_k(m, \chi) = \sum_{d|m} \chi(d)d^k, \quad \tilde{\sigma}_k(m, \chi) = \sum_{d|m} \chi \left(\frac{m}{d}\right)d^k.
\]

Let \(a_p = \text{ord}_p(m)\). For any quadratic character \(\chi\) modulo \(\Delta\) we have

\[
\tilde{\sigma}_k(m, \chi) = m^k \sum_{p|m} \frac{1 - (\chi(p)p^{-k})(a_p+1)}{1 - \chi(p)p^{-k}} \geq m^k \prod_{p|m, (p, \Delta) = 1} (1 - p^{-k}).
\]
This is because
\[ \tilde{\sigma}_k(m, \chi) = \sum_{d | m} \chi(d) \left( \frac{m}{d} \right)^k = m^k \sum_{d | m} \chi(d) d^{-k} \]
and
\[ 1 - (\chi(p)p^{-k})^{(a_p+1)} \geq \frac{1 - p^{-k(a_p+1)}}{1 + p^{-k}} \geq \frac{1 - p^{-2k}}{1 + p^{-k}} = 1 - p^{-k}. \]

If \((m, \Delta) = 1\) then \(\tilde{\sigma}_k(m, \chi) = \chi(m)\sigma_k(m, \chi)\) since \(\chi\) is a real character. Moreover for any prime divisor \(p\) of the module \(\Delta\) of \(\chi\)
\[ \tilde{\sigma}_k(p^{\alpha}m_1, \chi) = p^{\alpha k} \tilde{\sigma}_k(m_1, \chi), \quad \sigma_k(p^{\alpha}m_1, \chi) = \sigma_k(m_1, \chi). \]
Therefore
\[ N_{D_6}(2m) \geq 60\tilde{\sigma}_2(m, \chi_4) > 60(2^{-2})^{-1}m^2 = \frac{480}{\pi^2} m^2. \quad (30) \]

Next we have to estimate from above the Dirichlet series
\[ \sum_{n \geq 1} b_n(\Delta) \frac{1}{n^s} = \frac{\zeta(s)L(s, \Delta)}{\zeta(2s)} \]
(see (21)) for \(s = 2\). If \((n, \Delta) = 1\) then
\[ b_n(\Delta) \leq b_n(1) = 2^{\rho(n)}, \]
where \(\rho(n)\) is the number of prime divisors of \(n\), with equality if and only if \((\frac{\Delta}{p}) = 1\) for any odd prime divisor of \(n\) and \((\frac{\Delta}{2}) = 1\) if \(n\) is even. If in \(n\) there is at least one non-residue modulo \(\Delta\) then \(b_n(\Delta) = 0\). Therefore if \((p, \Delta) = 1\) (it might be that \(p = 2\)) then the local \(p\)-factor of the Dirichlet series is equal to
\[ 1 + 2 \sum_{m \geq 1} p^{-ms} = \frac{p^s + 1}{p^s - 1}. \quad (31) \]
Let us assume that \(\Delta = p^{2k}\Delta'\) (it might be that \(p = 2\)) with \((p, \Delta') = 1\). Considering the congruence class of \(b_{p^m}(p^{2k}\Delta')\) for all powers of \(p\) we see that the local \(p\)-factor of the Dirichlet series equals
\[ 1 + \sum_{m=1}^{2k} \frac{p | \frac{p^m}{p^{ms}} |}{p^{ms}} + 2p^k \sum_{m \geq 2k+1} p^{-ms}. \quad (32) \]
If \(\Delta = p^{2k+1}\Delta'\) then the local factor is smaller: the last term in (32) \(2p^k \sum_{m \geq 2k+1} p^{-ms}\), is replaced by one summand, \(p^{k-(2k+1)s}\). A direct calculation shows that for \(s = 2\) the regular factor (31) is larger than the non-regular factor (32) for any prime \(p \geq 2\). Therefore
\[ \frac{\zeta(2)L(2, \Delta)}{\zeta(4)} \leq \prod_p \frac{p^2 + 1}{p^2 - 1} = \frac{\zeta(2)^2}{\zeta(4)} = \frac{5}{2}. \]
The next step is an estimation from above of the 2-factor in \( N_{A_1 \oplus D_4}(2m) = r(m, S_{1,4}) \) and the 2- and 3-factors in \( N_{A_5}(2m) = r(m, \frac{1}{2} A_5) \). Elementary calculation using (26) gives us

\[
\frac{1 - \chi_D(2)2^{-2}}{1 - 2^{-4}} \alpha_2(m, S_{1,4}) \leq \frac{5}{4},
\]

with equality if \( D \equiv 5 \mod 8 \) and \( m \) is odd.

For the local 3-factor in \( \frac{1}{2} A_5 \) we obtain (using (28))

\[
\frac{1 - \chi_D(3)3^{-2}}{1 - 3^{-4}} \alpha_3(m, \frac{1}{2} A_5) \leq \frac{11}{12}
\]

with equality if \( m = 3m' \), where \( m' \equiv 2 \mod 3 \).

For the local 2-factor in \( \frac{1}{2} A_5 \) we obtain

\[
\frac{1 - \chi_D(2)2^{-2}}{1 - 2^{-4}} \alpha_2(m, \frac{1}{2} A_5) \leq \frac{10}{7}.
\]

In this case we must analyse the case when \( m = 2^a m' \) and \( b = \lfloor \frac{a}{2} \rfloor \) goes to infinity (see (29)). If \( D \equiv 0 \mod 4 \) or \( \equiv 5 \mod 8 \) then the local density tends to its supremum as \( b \) tends to infinity. This value is equal to \( \frac{15}{14} \). Therefore the left-hand side of (35) is smaller than \( \frac{10}{7} \). If \( D \equiv 1 \mod 8 \) then \( \alpha_2 \) takes its maximal values \( \frac{35}{32} \) for \( b = 0 \). In this case the left-hand side of (35) is equal to \( \frac{35}{32} \).

Now we can combine all our estimates. We have

\[
N_{A_1 \oplus D_4}(2m) \leq 50m^{3/2}, \quad N_{A_5}(2m) \leq \frac{2200}{21\sqrt{3}} m^{3/2}.
\]

Using (30) we obtain that the inequalities (17) and (18) of Theorem 4.5 and Proposition 5.5 are valid for \( m > 102 \) and for \( m > 71 \) respectively. For many \( m \) smaller or equal to 102 we can write a better estimate for the number of representations. But we can use the exact formulae for the theta series of \( D_6, A_1 \oplus D_4 \) and \( A_5 \) in terms of Jacobi theta series in order to check the inequality for \( m \leq 102 \).

The theta series of the lattice \( A_n \) is given by the formula (see [CS, Ch. 4, (56)])

\[
\theta_{A_n}(\tau) = \sum_{k=0}^{n-1} \vartheta_3(\tau, \frac{k}{n})^6, \quad \frac{6 \vartheta_3(6\tau)}{\vartheta_3(\tau)},
\]

where

\[
\vartheta_3(\tau, z) = \sum_{n \in \mathbb{Z}} \exp(\pi i(n^2 \tau + 2nz)),
\]

and \( \vartheta_3(\tau) = \vartheta_3(\tau, 0) \). For the lattice \( D_n \) one has (see [CS, Ch. 4, (87), (10)]) that

\[
\theta_{D_n}(\tau) = \frac{1}{2}(\vartheta_3(\tau)^n + \vartheta_3(\tau + 1)^n).
\]
Using these formulae we can compute the first 102 Fourier coefficients of the function

$$5\theta_{D_6} - 30\theta_{A_1 \oplus D_4} - 16\theta_{A_5}.$$  

(This is a calculation with formal power series which we did using PARI.) We find that these coefficients are negative exactly for $d < 20$ and $d \neq 17$. Hence the first inequality of the proposition holds as stated. Repeating the same calculation with 6 instead of 5 we obtain the second inequality. \(\square\)

We have now proved a slightly weakened version of Theorem 4.1. To obtain the full result we need the following observation.

**Proposition 5.6** For $d = 12, 13, 14, 15, 16, 18$ and $19$ there exist vectors $l_d \in E_7$ that satisfy $l_d^2 = 2d$ that are orthogonal to at least 2 and at most 14 roots. For $d = 9$ and $d = 11$ there exist vectors of length $l^2 = 2d$ that are orthogonal to exactly 16 roots.

**Proof.** These were found by a computer search. We give one example in each case. We express the vectors in terms of the simple roots $v_i$, $1 \leq i \leq 7$ which are given in terms of the standard basis $e_1, \ldots, e_8$ of $\mathbb{Q}^8$ by

$$v_i = e_{i+2} - e_{i+1} \quad \text{for } 1 \leq i \leq 6,$$

$$v_7 = \frac{1}{2}(e_1 + e_2 + e_3 + e_4) - \frac{1}{2}(e_5 + e_6 + e_7 + e_8)$$

(see \[Bou\]). The examples are shown in Table 1: the vector $l_d = \sum \lambda_d, v_i$ with $\lambda_d = (\lambda_d,1, \ldots, \lambda_d,7) \in \mathbb{Z}^7$ is orthogonal to exactly $2p_d$ roots of $E_7 = \sum_{i=1}^7 \mathbb{Z}v_i \subset \mathbb{Q}^8$. There are other vectors with the required properties (for instance, we found one with $d = 19$ and $p = 7$), but none for smaller $d$. \(\square\)

| $d$ | $p$ | $\lambda_d$ |
|-----|-----|-------------|
| 9   | 8   | -1,2,3,1,2,1,3 |
| 11  | 8   | 3,3,0,-1,-2,-1,0 |
| 12  | 7   | 2,1,2,-2,0,0,1 |
| 13  | 7   | 2,3,-1,1,0,0,-1 |
| 14  | 6   | 2,0,3,0,2,1,1 |
| 15  | 7   | 1,-2,0,2,4,2,0 |
| 16  | 6   | 1,0,-1,3,0,0,-2 |
| 18  | 5   | 3,2,3,2,0,0,-2 |
| 19  | 6   | 2,3,2,-3,-4,-2,1 |

Table 1: Short vectors in $E_7$ orthogonal to few roots
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