RATIONAL CHEREDNIK ALGEBRAS AND HILBERT SCHEMES

I. GORDON AND J. T. STAFFORD

Dedicated to Mike Artin on the occasion of his 70th birthday

Abstract. Let $H_c$ be the rational Cherednik algebra of type $A_{n-1}$ with spherical subalgebra $U_c = eHce$. Then $U_c$ is filtered by order of differential operators, with associated graded ring $\text{gr } U_c = \mathbb{C}[\mathfrak{h} \oplus \mathfrak{h}^*]^W$ where $W$ is the $n$-th symmetric group. We construct a filtered $\mathbb{Z}$-algebra $B$ such that, under mild conditions on $c$:

- the category $B\text{-qgr}$ of graded noetherian $B$-modules modulo torsion is equivalent to $U_c\text{-mod}$;
- the associated graded $\mathbb{Z}$-algebra $\text{gr } B$ has $\text{gr } B\text{-qgr} \cong \text{Coh Hilb}(n)$, the category of coherent sheaves on the Hilbert scheme of points in the plane.

This can be regarded as saying that $U_c$ simultaneously gives a noncommutative deformation of $\mathfrak{h} \oplus \mathfrak{h}^*/W$ and of its resolution of singularities $\text{Hilb}(n) \to \mathfrak{h} \oplus \mathfrak{h}^*/W$. As the companion paper [GS] shows, this result is a powerful tool for studying the representation theory of $H_c$ and its relationship to Hilb($n$).

Contents

1. Introduction 2
2. Rational Cherednik algebras 6
3. Morita equivalence of Cherednik algebras 9
4. The Hilbert scheme 17
5. $\mathbb{Z}$-algebras 23
6. The main theorem 25
7. Tensor product filtrations 37
Appendix A. Graded projective modules 39
Appendix B. Another module 41
Index of Notation 45
References 45

1991 Mathematics Subject Classification. 14C05, 32S45,16S80, 16D90.

Key words and phrases. Cherednik algebra, Hilbert scheme, resolution of quotient singularities, equivalence of categories.

The first author was supported by the Nuffield Foundation Grant NAL/00625/A and the Leverhulme trust. He would like to thank the University of Washington and the University of California at Santa Barbara for their hospitality while parts of this paper were written. The second author was supported in part by the NSF through the grants DMS-9801148 and DMS-0245320. Part of this research was conducted while he was visiting the Mittag-Leffler Institute and he would like to thank them for their hospitality and financial support.

1
1. Introduction

1.1. This is the first of two closely related papers on rational Cherednik algebras. In their short history, Cherednik algebras have been influential in a surprising range of subjects: for example they have been used to answer questions in integrable systems, combinatorics, and symplectic quotient singularities (see [BEG1, Go2, BFG, GK]). In this paper we strengthen the connections between Cherednik algebras and geometry by showing that they can be regarded as noncommutative deformations of Hilbert schemes of points in the plane. In the sequel [GS] this will be used to show the close relationship between modules over the Cherednik algebra and sheaves on the Hilbert scheme as well as to answer various open problems about these modules.

1.2. Fix \( c \in \mathbb{C} \). We assume throughout the paper that \( c \not\in \frac{1}{2} + \mathbb{Z} \) and, for simplicity, we will also assume that \( c \not\in \mathbb{R}_{\leq 0} \) in this introduction, see (3.13) and (3.14) for the more general case.

Let \( H_c = H_{1,c} \) be the rational Cherednik algebra of type \( A_{n-1} \) with spherical subalgebra \( U_c = eH_c e \). The formal definition of \( H_c \) is given in (2.1) but one may regard it as a deformation of the twisted group ring \( D(\mathfrak{h}) \ast W \), where \( D(\mathfrak{h}) \) is the ring of differential operators on \( \mathfrak{h} \cong \mathbb{C}^{n-1} \) with the natural action of the symmetric group \( W = \mathfrak{S}_n \). The algebra \( U_c \) is then the corresponding deformation of the fixed ring \( D(\mathfrak{h})^W \).

The algebras \( U_c \) and \( H_c \) have a natural filtration by order of differential operators with associated graded rings \( \text{gr} U_c \cong \mathbb{C}[\mathfrak{h} \oplus \mathfrak{h}^*]^W \) and \( \text{gr} H_c \cong \mathbb{C}[\mathfrak{h} \oplus \mathfrak{h}^*] \ast W \). Thus we may also regard \( U_c \) as a deformation of \( \mathbb{C}[\mathfrak{h} \oplus \mathfrak{h}^*]^W \). In this introduction we will mostly be concerned with \( U_c \), but since \( U_c \) and \( H_c \) are Morita equivalent (Corollary 3.13) the results we prove for \( U_c \) also apply to \( H_c \).

It is well-known that \( \mathfrak{h} \oplus \mathfrak{h}^*/W \) has a crepant resolution \( \text{Hilb}(n) \to \mathfrak{h} \oplus \mathfrak{h}^*/W \), where \( \text{Hilb}(n) \) is a variant on the Hilbert scheme of \( n \) points in the plane (see (4.9) for the formal definition). The ring \( U_c \) has finite global homological dimension (see Corollary 3.15) and so one should expect that it has the properties of a smooth deformation of \( \mathbb{C}[\mathfrak{h} \oplus \mathfrak{h}^*]^W \); in other words its properties should be more closely related to those of \( \text{Hilb}(n) \) than to \( \mathfrak{h} \oplus \mathfrak{h}^*/W \). Hints of this have been reported in [Go2] and [BEG2]: finite dimensional \( H_c \)-modules deform the sections of some remarkable sheaves on \( \text{Hilb}(n) \). The main aim of this paper is to formalise this idea by showing that there is a second way of passing to associated graded objects that maps \( U_c\text{-mod} \) precisely to \( \text{Coh}(\text{Hilb}(n)) \).

1.3. We take our cue from the theory of semisimple Lie algebras. When \( n = 2 \), \( U_c \) is isomorphic to a factor of \( U(\mathfrak{sl}_2) \) [EG, Section 8] and, for all \( n \), the properties of \( U_c \) are similar to those of \( U(\mathfrak{g})/P \), where \( P \) is a minimal primitive ideal in the enveloping algebra of a complex semisimple Lie algebra \( \mathfrak{g} \) (see, for example [Gi, GGOR, Gu]). The intuition from the last paragraph not only holds for enveloping algebras but can also...
be formalised through the Beilinson-Bernstein equivalences of categories. This gives a diagram

\[
\begin{array}{ccc}
D_B & \xleftarrow{\sim} & U(\mathfrak{g})/P \\
\text{gr} & \downarrow & \text{gr} \\
\mathcal{O}_{T^*B} & \xleftarrow{\tau} & \mathcal{O}(\mathcal{N})
\end{array}
\]

where \( B = G/B \) is the flag variety, the primitive ideal \( P \) has trivial central character and \( \tau : T^*B \to \mathcal{N} \) is the Springer resolution of the nullcone \( \mathcal{N} \). The Morita equivalence from the sheaf of differential operators \( D_B \) to \( U(\mathfrak{g})/P \) is obtained by taking global sections under the identification \( U(\mathfrak{g})/P \cong D_B \).

Ginzburg has raised the question of whether a similar phenomenon holds for Cherednik algebras (see [GK, Conjecture 1.6] for a variant on this conjecture). In other words, can one complete the following diagram?

\[
\begin{array}{ccc}
? & \xleftarrow{\sim} & U_c \\
\text{gr} & \downarrow & \text{gr} \\
\mathcal{O}_{\text{Hilb}(n)} & \xleftarrow{\tau} & \mathcal{O}(\mathfrak{h} \oplus \mathfrak{h}^*/W)
\end{array}
\]

The main result of the paper gives a positive answer to this question. Given a graded ring \( R \), we write \( R\text{-qgr} \) for the quotient category of noetherian graded \( R \)-modules modulo those of finite length.

**1.4. Main Theorem.** There exists a graded ring \( B \), filtered by order of differential operators, such that

1. there is an equivalence of categories \( U_c \text{-mod} \cong B\text{-qgr} \);
2. there is an equivalence of categories \( \text{gr } B\text{-qgr} \cong \text{Coh}(\text{Hilb}(n)) \).

**1.5.** The construction of \( B \) needs some explanation. For \( n > 2 \), it can be shown that the Hilbert scheme \( \text{Hilb}(n) \) is not a cotangent bundle, so we cannot use sheaves of differential operators as a non-commutative model. Instead we take as our starting point Haiman’s description of \( \text{Hilb}(n) \) as a blow-up of \( \mathfrak{h} \oplus \mathfrak{h}^*/W \) and deform this to a non-commutative setting. Set \( A^0 = \mathcal{O}(\mathfrak{h} \oplus \mathfrak{h}^*/W) \) with ideal \( I = A^1 \delta \), where \( \delta \) is the discriminant and \( A^1 = \mathbb{C}[\mathfrak{h} \oplus \mathfrak{h}^*/W]^\ast \) the module of anti-invariants. Then [Ha1, Proposition 2.6] proves that \( \text{Hilb}(n) = \text{Proj } A \) where \( A = A^0[\delta I] \) is the Rees ring of \( I \) (see Section 4 for the details).

Unfortunately one cannot construct \( B \) as an analogous Rees ring over \( U_c \), since \( U_c \) is a simple ring for generic values of \( c \). We circumvent this problem by using \( \mathbb{Z}\text{-algebras} \) (see Section 5). Specifically, the ring \( B \) from Theorem 1.4 is an algebra \( B = \bigoplus_{i,j \geq 0} B_{ij} \) whose multiplication is defined in matrix fashion: \( B_{ij}B_{jk} \subseteq B_{ik} \) but \( B_{ij}B_{tk} = 0 \) when \( j \neq \ell \). The diagonal terms are just \( B_{ii} = U_{c+i} \) while the off-diagonal terms \( B_{ij} \) are given as the appropriate tensor products of the \( (U_{d+1}, U_d) \)-bimodules \( Q^{d+1}_d = eH_{d+1} \delta e \). The shift functors \( S_d : U_d \text{-mod} \to U_{d+1} \text{-mod} \) given by tensoring with \( Q^{d+1}_d \) are important operators in the theory of Cherednik algebras and have already played a crucial role in combinatorics and representation theory; see, for example, [BEG2, BEG1, Go2]. A good way to think of the functor \( S_d \) is as the analogue of the translation functor [BG] from Lie theory.
In order to have control over $B$ we need to know that the $Q_d^{d+1}$ are progenerators for all $d \in c + \mathbb{N}$; equivalently that the $S_d$ are Morita equivalences. This is a conjecture from [GGOR, Remark 5.17] which we answer with:

1.6. Theorem. [Corollary 3.13] The shift functor $S_d$ is a Morita equivalence for all $d \in c + \mathbb{N}$.

The significance of this result is that $B$ now has rather pleasant properties; in particular Theorem 1.4(1) is an easy consequence. For the second assertion of Theorem 1.4, we note that it is easy to obtain a $\mathbb{Z}$-algebra $\hat{A} = \bigoplus_{i \geq j \geq 0} A_{ij}$ from the graded algebra $A = \bigoplus_{k \geq 0} I_k$ for which $A_{qgr} \simeq \hat{A}_{qgr}$. One simply takes $A_{ij} = I^{i-j}$ for each $i, j$. Thus the main step in the proof of Theorem 1.4 is given by:

1.7. Proposition. [Theorem 6.4] Under the filtration induced from the order filtration of differential operators, $\text{gr } B_{ij} \cong A_{i-j} = I^{i-j}$ and so $\text{gr } B \cong \hat{A}$ as $\mathbb{Z}$-algebras.

In this result the inclusion $I^{i-j} \subseteq \text{gr } B_{ij}$ is straightforward. The opposite inclusion is much more subtle as it is difficult to keep close control of the filtration on $B_{ij}$. Our proof leans heavily on the work of Haiman in [Ha3] and [Ha4] surrounding the $n!$ and polygraph theorems and the strategy is outlined in more detail in (6.6).

1.8. Applications. Theorem 1.4 gives a powerful technique for relating $H_c$- or $U_c$-modules to sheaves on Hilb(n): given a $U_c$-module $M$ with a good filtration $\Lambda$ we obtain a filtered object $(\hat{M}, \Lambda) \in B_{qgr}$ by tensoring with $B$ and then a coherent sheaf $\Phi_\Lambda(M) \in \text{Coh}(\text{Hilb}(n))$ by taking the associated graded module.

This process is studied in [GS] where we show there that the subtle combinatorics and geometry of Hilb(n) is reflected in the representation theory of $U_c$ and $H_c$. Let $\Delta_c(\mu)$ be the standard $H_c$-module corresponding to $\mu \in \text{Irrep}(W)$ (this is the analogue of a Verma module) with unique simple factor $L_c(\mu)$. These modules have a natural good filtration $\Lambda$ and we mention a couple of illustrative results from [GS].

- Suppose that $c = 1/n + k$ for $k \in \mathbb{N}$, so that $L_c(\text{triv})$ is the unique finite dimensional simple $H_c$-module. Then $\Phi_\Lambda(eL_c(\text{triv})) \cong \mathcal{O}_{Z_n} \otimes \mathcal{L}^k$, where $Z_n = \tau^{-1}(0)$ is the punctual Hilbert scheme and $\mathcal{L} = \mathcal{O}_{\text{Hilb}(n)}(1)$ is the Serre twisting sheaf.

- For any $c$, the characteristic cycle of $\Phi_\Lambda(e\Delta_c(\mu))$ equals $\sum \Lambda K_{\mu \Lambda}[\Lambda]$, where $K_{\mu \Lambda}$ are Kostka numbers and the $\Lambda$ are particular irreducible components of $\tau^{-1}(\mathfrak{h} \oplus \{0\}/W)$.

The first of these results is used in [GS] to show that the natural bigraded structure on $\text{gr } A(eL_{1/n+k})$ coincides with that on $H^0(Z_n, \mathcal{L}^k)$, thus confirming a conjecture of [BEG2]. The second of these results illustrates the subtlety of $\Phi$: if one passes directly from $U_c$ to $\text{gr } U_c \cong \mathbb{C}[\mathfrak{h} \oplus \mathfrak{h}^*]^{W}$ then $\text{gr } A(e\Delta_c(\mu)) \cong \mathbb{C}[\mathfrak{h}] \otimes \mu$ for any $\mu$ and $c$. Thus the support variety of $\text{gr } A e\Delta_c(\mu)$ is independent of $\mu$.

We prove one such correspondence in this paper. Let $\mathcal{P}$ denote the Procesi bundle on Hilb(n), the vector bundle of rank $n!$ coming from Haiman’s $n!$ theorem, see (4.10). Then Corollary 6.22 proves:

1.9. Corollary. If $eH_c$ is given the order filtration $\Lambda$, then $\Phi_\Lambda(eH_c) = \mathcal{P}$.
1.10. One reason why Theorem 1.4 provides a strong bridge between Hilbert schemes and Cherednik algebras is that the construction of $B$ carries within it key elements of both theories. For instance, we have already mentioned that the shift functor $S_c$ is an analogue of the translation functor from Lie theory. It is also the analogue of the shift functor in $\text{Coh}(\text{Hilb}(n))$ given by tensoring with $\mathcal{O}_{\text{Hilb}(n)}(1)$. Indeed, given a $U_c$-module $M$ with a good filtration $\Lambda$, it is easy to show that $\Phi_{\Gamma}(Q_{c+1}^c \otimes M) = \mathcal{O}_{\text{Hilb}(n)}(1) \otimes \Phi_{\Lambda}(M)$, for the appropriate filtration $\Gamma$ (see [GS]).

Similarly, Corollary 1.9 can be interpreted as saying that $H_c$ is a noncommutative analogue of the isospectral scheme $X_n$, as defined in (4.10) (see (6.23) for further details).

1.11. The $\mathbb{Z}$-algebra has the virtue that it exists whenever one has an analogue of the translation principle; that is, one has algebras $R_i$ and generative $(R_i, R_{i+1})$-bimodules $Q_{i,i+1}$ (these algebras can also be indexed by more general lattices than $\mathbb{Z}$). One can then construct a $\mathbb{Z}$-algebra as we have done and Theorem 1.4(1) will still hold. It is not clear when Theorem 1.4(2) will hold and, even when it is true, it will undoubtedly be rather subtle.

Hilbert schemes realise crepant resolutions for the symplectic quotient singularity $((\mathbb{C}^2)^n/G)$ whenever $G$ is the wreath product of a finite subgroup of $SL_2(\mathbb{C})$ with the symmetric group $W$, see [Wa, Theorem 4.2]. We believe that our methods will generalise to the symplectic reflection algebras $H_c(G) = H_{1,c}(G)$ associated with $((\mathbb{C}^2)^n, G)$ to give non-commutative deformations of those Hilbert schemes. Even when there is no crepant resolution of such a singularity (by [GK] this happens for Weyl groups $G$ of types other than $A$ and $B$) the $\mathbb{Z}$-algebra associated to $H_c(G)$ will still contain interesting information, as [Go2] demonstrates.

For a Weyl group, the analogue of Theorem 1.6 is at least known for sufficiently large values of the defining parameter $c$ [BEG2, Proposition 4.3], but little is known for small values of $c$.

The translation principle obviously holds for factors of enveloping algebras of semisimple Lie algebras and we can prove an analogue of Theorem 1.4 in this case. However, the proof uses nontrivial Lie theoretic results, notably the Beilinson-Bernstein equivalence of categories, and it is unclear whether this approach carries information that cannot be obtained from that equivalence. It would be interesting to see if the recent work [BK, Ta] on the Beilinson-Bernstein equivalence for quantised enveloping algebras can be understood in a $\mathbb{Z}$-algebra framework.

1.12. The paper is organised as follows. In Section 2 we recall the needed facts about rational Cherednik algebras, while in Section 3 we prove Theorem 1.6. In Section 4 we describe some of Haiman’s work on Hilbert schemes, adapted to the variety $\text{Hilb}(n)$, and use it to describe various Poincaré series that will be needed in the proof of Theorem 1.4. Section 5 proves the results about $\mathbb{Z}$-algebras that were mentioned earlier in this introduction. Section 6 is the heart of the paper: in it we prove Theorem 1.4(2). This is derived from an analogous result about the associated graded module of $B_{k_0} \otimes_{U_c} eH_c$ that also implies Corollary 1.9. Section 7 then gives a reinterpretation of Theorem 1.4 in terms of a tensor product filtration of $B_{ij}$. In Appendix A we prove the following result that may be of independent interest: Suppose that
\( R = \bigoplus_{i \geq 0} R_i \) is an \( \mathbb{N} \)-graded algebra over a field \( k \), with \( R_0 = k \). If \( P \) is a right \( R \)-module that is both graded and projective, then \( P \) is graded-free in the sense that \( P \) has a free basis of homogeneous elements. This is a graded analogue of a classic result from [Ka] for which we do not know a reference.

1.13. Acknowledgement. We would like to thank Victor Ginzburg for bringing his conjecture to our attention, since it really formed the starting point for this work. We would also like to thank Tom Nevins and Catharina Stroppel for suggesting many improvements to us.

2. Rational Cherednik algebras

2.1. In this section we define the rational Cherednik algebras (which will always be of type \( A \) in this paper) and give some of the basic properties that will be needed in the body of the paper.

Let \( W = S_n \) be the symmetric group on \( n \) letters, regarded as the Weyl group of type \( A_{n-1} \) acting on its \((n-1)\)-dimensional representation \( h \subset \mathbb{C}^n \) by permutations. Let \( S = \{ s = (i, j) \mid i < j \} \subset W \) denote the reflections, with reflecting hyperplanes \( \alpha_s = 0 \). We make similar definitions for \( h^* \) and normalise \( \alpha_s^\vee \in h^* \) so that \( \alpha_s(\alpha_s^\vee) = 2 \).

Given \( c \in \mathbb{C} \), the rational Cherednik algebra of type \( A_{n-1} \) is the \( \mathbb{C} \)-algebra \( H_c \) generated by the vector spaces \( h \) and \( h^* \) and the group \( W \) with defining relations

\[
wxw^{-1} = w(x), \quad wyw^{-1} = w(y), \quad \text{for all } y \in h, x \in h^*, w \in W
\]

\[
x_1x_2 = x_2x_1, \quad y_1y_2 = y_2y_1, \quad \text{for all } y_i \in h, x_j \in h^*
\]

\[
yx - xy = x(y) - \sum_{s \in S} \alpha_s(y)x(\alpha_s^\vee)s, \quad \text{for all } y \in h, x \in h^*.
\]

We should note that the definition of the Cherednik algebra is not uniform throughout the literature. The definition we are using agrees with that in [BEG1, BEG2, EG, Gu] but \textit{not} that from [GGOR] where our constant \( c \) equals \(-k_1\) for their constant \( k_1 \) (see [GGOR, Remark 3.1]).

2.2. We write the coordinate ring of an affine variety \( V \) as \( \mathbb{C}[V] \). By [EG, Theorem 1.3], the subalgebra of \( H_c \) generated by \( h^* \) can and will be identified with \( \mathbb{C}[h] \), while \( h \) generates a copy of \( \mathbb{C}[h^*] \) inside \( H_c \) and the elements \( w \in W \) span a copy of the group algebra \( \mathbb{C}W \) in \( H_c \). Fix once and for all dual bases \( \{ x_i \} \) and \( \{ y_i \} \) of \( h^* \) and \( h \) respectively; thus \( \mathbb{C}[h] = \mathbb{C}[x_1, \ldots, x_{n-1}] \) and \( \mathbb{C}[h^*] = \mathbb{C}[y_1, \ldots, y_{n-1}] \).

By [EG, Theorem 1.3] there is a Poincaré-Birkhoff-Witt isomorphism of \( \mathbb{C} \)-vector spaces

\[
\mathbb{C}[h] \otimes_\mathbb{C} \mathbb{C}W \otimes_\mathbb{C} \mathbb{C}[h^*] \cong H_c.
\]

Filter \( H_c \) by \( \text{ord}^0 H_c = \mathbb{C}[h] \ast W \), \( \text{ord}^1 H_c = h \ast \text{ord}^0 H_c \) and \( \text{ord}^i H_c = (\text{ord}^1 H_c)^i \) for \( i > 1 \), and define the associated graded ring to be \( \text{ogr} H_c = \bigoplus \text{ogr}^n H_c \), where \( \text{ogr}^n H_c = \text{ord}^n H_c / \text{ord}^{n-1} H_c \). Then (2.2.1) is equivalent to the assertion that \( \text{ogr} H_c \) is isomorphic to the skew group ring \( \mathbb{C}[h \oplus h^*] \ast W \) defined by \( \sigma f = \sigma(f)\sigma \), for \( \sigma \in W \) and \( f \in \mathbb{C}[h \oplus h^*] \).
2.3. The Dunkl-Cherednik representation. Let $\delta \in \mathbb{C}[h]$ denote the discriminant polynomial $\delta = \prod_{s \in S} \alpha_s$. Thus $\delta$ transforms under $W$ by the sign representation and $h^{\text{reg}} = h \setminus \{ \delta = 0 \}$ is the subset of $h$ on which the action of $W$ is free. By [EG, Proposition 4.5] there is an injective algebra morphism $\theta_c : H_c \to D(h^{\text{reg}}) \ast W$, where $D(Z)$ denotes the ring of differential operators on an affine variety $Z$. Under $\theta_c$ the elements of $\mathbb{C}[h]$ are identified with the multiplication operators while, by [EG, p.280] and in the notation of (2.2), $y_i \in \mathfrak{h}$ is sent to the Dunkl operator

$$\theta_c(y_i) = \partial_i - \sum_{s \in S} \alpha_s(y_i) \alpha_s^{-1}(1 - s), \quad \text{where } \partial_i = \partial/\partial x_i. \tag{2.3.1}$$

Since $\delta$ acts ad-nilpotently on $D(h^{\text{reg}}) \ast W$, the set $\{ \delta^n \}$ forms an Ore set in that ring. As observed in [BEG1, p.288]), $\theta_c$ becomes an isomorphism on inverting $\delta$; that is,

$$H^{\text{reg}}_c = H_c[\delta^{-1}] \cong D(h^{\text{reg}}) \ast W. \tag{2.3.2}$$

For any variety $Z$, there is a natural filtration on $D(Z)$ by order of operators and this induces a filtration on $D(h^{\text{reg}}) \ast W$ and its subalgebras by defining elements of $W$ to have order zero. If $R$ is a subalgebra (or submodule) of $D(h^{\text{reg}}) \ast W$, we write the operators of order $\leq n$ as $\text{ord}^n(R)$. When $R = H_c$, $\text{ord}$ is clearly the same filtration as that defined in (2.2). The associated graded ring of $R$ will be written $\text{ogr}(R) = \bigoplus \text{ogr}^n(R)$, where $\text{ogr}^n(R) = \text{ord}^n(R)/\text{ord}^{n+1}(R)$, and the resulting graded structure of $\text{ogr}(R)$ will be called the order or grading. (This will be only one of several filtrations used in this paper.)

2.4. The rings of differential operators $D(h)$ and $D(h^{\text{reg}})$ also have a graded structure, given by the adjoint action $[E, -]$ of the Euler operator $E = \sum x_i \partial_i \in D(h)$. We will call this the Euler grading and write $E$-deg for the corresponding degree function; thus $E$-deg $x_i = 1$ and $E$-deg $\partial_i = -1$. Since $E \in D(h)^W$, $E$ commutes with $W$ in $D(h^{\text{reg}}) \ast W$ and so this grading extends to that ring with $E$-deg $W = 0$. By inspection, (2.3.1) implies that the $y_i$ also have degree $-1$ and so each $H_c$ is also graded under $[E, -]$ and we continue to call this the Euler grading.

It is well-known and easy to check that the $E$-grading is compatible with the order filtration on $D(h^{\text{reg}}) \ast W$, in the sense that $[E, \text{ord}^n D(h^{\text{reg}}) \ast W] \subseteq \text{ord}^n D(h^{\text{reg}}) \ast W$ for all $n \geq 0$. We therefore obtain an induced grading, again called the $E$-grading, on the associated graded ring $\text{ogr} D(h^{\text{reg}}) \ast W \cong \mathbb{C}[h^{\text{reg}} \oplus h^*] \ast W$. Clearly this is again given by $E$-deg $h^* = 1$ (which we define to mean that $E$-deg $x = 1$ for every $0 \neq x \in h^*$) while $E$-deg $h = -1$ and $E$-deg $W = 0$.

One should note that, in general, $E \notin H_c$. However, there is a natural element in $H_c$ that has the same adjoint action. Indeed, let

$$h = h_c = \frac{1}{2} \sum_{i=1}^{n-1} (x_i y_i + y_i x_i) \in H_c. \tag{2.4.1}$$

This is independent of the choice of basis. By [BEG1, (2.6)] we have

$$[h, x] = x, \quad [h, y] = -y, \quad \text{and } [h, w] = 0 \quad \text{for all } x \in h^*, y \in h \text{ and } w \in W. \tag{2.4.2}$$
Thus commutation with $\mathbf{h}$ also induces the Euler grading on $H_c$.

2.5. The spherical subalgebra. Let $e \in \mathbb{C}W$ be the trivial idempotent and $e_- \in \mathbb{C}W$ be the sign idempotent; thus $e = |W|^{-1} \sum_{w \in W} w$ and $e_- = |W|^{-1} \sum_{w \in W} \text{sign}(w)w$. The main algebra of study in this paper is not the Cherednik algebra itself, but its spherical subalgebra $U_c = eH_c e$ and the related algebra $U_c^- = e_- H_c e_-$. We will use frequently and without comment that $\delta$ is a $W$-anti-invariant and so $e_- \delta = \delta e$.

Also, as $E$-deg $W = 0$, both $U_c$ and $U_c^-$ have an induced $E$-graded structure.

2.6. Partitions. The rest of this section is devoted to the definition and basic properties of category $\mathcal{O}_c$. Since its structure depends upon the combinatorics of $W$-representations, we begin with the relevant notions from that theory.

We write a partition of $n$ as $\mu = (\mu_1 \geq \mu_2 \geq \cdots \geq \mu_l > 0)$, with the understanding that $\mu_i = 0$ for $i > l$. The Ferrers diagram of $\mu$ is the set of lattice points $d(\mu) = \{(i, j) \in \mathbb{N} \times \mathbb{N} : j < \mu_i + 1\}$.

Following the French style, the diagram is drawn with the $i$-axis vertical and the $j$-axis horizontal, so the parts of $\mu$ are the lengths of the rows, and $(0, 0)$ is the lower left corner. The arm $a(x)$ and the leg $l(x)$ of a point $x \in d(\mu)$ denote the number of points strictly to the right of $x$ and above $x$, respectively. The hook length $h(x)$ is $1 + a(x) + l(x)$. For example:

\[
\begin{align*}
\mu &= (5, 5, 4, 3, 1) \\
a(x) &= 3, \quad l(x) = 2, \quad h(x) = 6.
\end{align*}
\]

The transpose partition $\mu^t$ is obtained from $\mu$ by exchanging the rows and columns of $\mu$.

We will always use the dominance ordering of partitions as in [Mac, p.7]; thus if $\lambda$ and $\mu$ are partitions of $n$ then $\lambda \geq \mu$ if and only if $\sum_{i=1}^{k} \lambda_i \geq \sum_{i=1}^{k} \mu_i$ for all $k \geq 1$.

Let $\text{Irr}(W)$ denote the set of simple $W$-modules, up to isomorphism. As usual, irreducible representations of $W$ will be parametrised by partitions of $n$. We use the ordering on $\text{Irr}(W)$ arising from the dominance ordering; thus, as in [Mac, Example 1, p.116], the trivial representation $\text{triv}$ is labelled by $(n)$ while the sign representation $\text{sign}$ is parametrised by $(1^n)$ and so $\text{triv} > \text{sign}$. Note that the operation on $\text{Irr}(W)$ given by tensoring by $\text{sign}$ corresponds to the transposition of partitions.

2.7. Category $\mathcal{O}_c$. (See [GGOR] and [BEG1, Definition 2.4].) Let $\mathcal{O}_c$ be the abelian category of finitely-generated $H_c$-modules $M$ which are locally nilpotent for the subalgebra $\mathbb{C}[\mathbf{h}^*] \subset H_c$. By [Gu, Theorem 3] $\mathcal{O}_c$ is a highest weight category.
Given \( \mu \in \text{irrep}(W) \), we define \( \Delta_c(\mu) \), an object of \( \mathcal{O}_c \) called the standard module, to be the induced module \( \Delta_c(\mu) = H_c \otimes_{\mathbb{C}[h^*]} W \mu \), where \( \mathbb{C}[h^*] \ast W \) acts on \( \mu \) by \( pw \cdot m = p(0)(w \cdot m) \) for \( p \in \mathbb{C}[h^*] \), \( w \in W \) and \( m \in \mu \). It is shown in [BEG1, Section 2] that each \( \Delta_c(\mu) \) has a unique simple quotient \( L_c(\mu) \), that the set \( \{L_c(\mu) : \mu \in \text{irrep}(W)\} \) provides a complete list of non-isomorphic simple objects in \( \mathcal{O}_c \) and that every object in \( \mathcal{O}_c \) has finite length. Note that it follows from the PBW Theorem 2.2.1 that the standard module \( \Delta_c(\mu) \) is a free left \( \mathbb{C}[h^*] \)-module of rank \( \dim(\mu) \).

2.8. The KZ functor. Let \( M \in \mathcal{O}_c \). Then its localisation \( M^{reg} = M[\delta^{-1}] \) at the powers of \( \delta \) is a \( W \)-equivariant \( D \)-module on \( h^{reg} \) in the sense that \( M^{reg} \) is a \( W \)-equivariant vector bundle on \( h^{reg} \) with a flat \( W \)-equivariant connection. On taking the germs of horizontal sections on \( h^{reg}/W \) we get a representation of the braid group \( B_n = \pi_1(\mathfrak{h}^{reg}/W) \). This representation factors through the Hecke algebra \( \mathcal{H}_q \) of \( W \) with parameter \( q = \exp(2\pi i) \) [GGOR, Theorem 5.13]. In this way we have the Knizhnik-Zamolodchikov functor \( \text{KZ} : \mathcal{O}_c \to \mathcal{H}_q \)-mod. There is an anti-involution \( \iota \) on \( \mathcal{H}_q \) induced by \( \iota(T_w) = T_{w^{-1}} \). Given a module \( V \) for \( \mathcal{H}_q \), the space \( V^* = \text{Hom}_{\mathcal{H}_q}(V, \mathbb{C}) \) becomes an \( \mathcal{H}_q \)-module via the rule \( h \cdot f(v) = f(\iota(h)v) \).

The images of the standard modules under \( \text{KZ} \) are known, [GGOR, Remark 6.9 and Corollary 6.10]. For \( c \in \mathbb{R}_{\geq 0} \) and \( \mu \in \text{irrep}(W) \)

\[
\text{KZ}(\Delta_c(\mu)) \cong S\mu(\mu)^*
\]

where \( S\mu(\mu) \) is the so-called Specht module associated to \( \mu \). (The dual module appears since the defining relations for the rational Cherednik algebra given in [GGOR] are normalised differently to (2.1); as remarked in (2.1), our parameter \( c \) corresponds to \( -k_1 \) in [GGOR].) Now suppose that \( M \in \mathcal{O}_c \) has a filtration

\[
0 = M_0 \subset M_1 \subset \cdots \subset M_{t-1} \subset M_t = M
\]

such that \( M_i/M_{i-1} \) is a standard module for all \( 1 \leq i \leq t \). If \( N \in \mathcal{O}_c \) and \( c \notin \frac{1}{2} + \mathbb{Z} \) then [GGOR, Proposition 5.9] implies that

\[
\text{Hom}_{\mathcal{H}_q}(N, M) = \text{Hom}_{\mathcal{H}_q}(\text{KZ}(N), \text{KZ}(M)).
\]

3. Morita equivalence of Cherednik algebras

3.1. A powerful technique in the theory of semisimple Lie algebras is the translation principle, given by tensoring with a finite dimensional module, in part because it gives an equivalence of categories between the \( \mathcal{O} \) categories (and the Harish-Chandra categories) corresponding to distinct central characters [BG]. One interpretation of this is that tensoring with a module of \( \mathfrak{t} \)-finite vectors gives a Morita equivalence between the corresponding factors of the enveloping algebra [JS, Corollary 4.13].

Although it does not involve finite dimensional modules, there is a natural analogue of this procedure for Cherednik algebras, given by the Heckman-Opdam shift functors defined in (3.2). These functors have proved useful in a number of papers (see, for example, [BEG1, BEG2, Go2]) and for particular values of \( c \) these functors are known to give equivalences of categories between \( H_c, U_c \) and \( U_{c+1} \) (see, for example,
Assume that the Theorem. begin with that case. The general case, proved in Corollary 3.13, will be an easy consequence.

3.2. Fix $c \in \mathbb{C}$ and keep the notation of (2.5). If we identify $H_c$ with its image in $D(h^{reg}) * W$ via the Dunkl operator (2.3.1) then, by [BEG2, Proposition 4.1], there is an identity

$$U_c = \delta^{-1}U_{c+1}\delta = e\delta^{-1}H_{c+1}\delta e.$$  

In particular, $Q^{c+1} = eH_{c+1}e - \delta = eH_{c+1}\delta e$ is a $(U_{c+1}, U_c)$-bi-submodule of $D(h^{reg}) * W$. The shift functors mentioned above are given by

$$S_c : U_c \text{-mod} \to U_{c+1} \text{-mod} : N \mapsto Q_c^{c+1} \otimes U_c N$$

and

$$\tilde{S}_c : H_c \text{-mod} \to H_{c+1} \text{-mod} : M \mapsto H_{c+1}e - \delta \otimes U_c e M.$$  

3.3. When $c$ is a positive real number, the Morita equivalence between $U_c$ and $U_{c+1}$ is given by $S_c$ and we begin with that case. The general case, proved in Corollary 3.13, will be an easy consequence.

**Theorem.** Assume that $c \in \mathbb{R}_{\geq 0}$ with $c \notin \frac{1}{2} + \mathbb{Z}$. Then both shift functors $\tilde{S}_c : H_c \text{-mod} \to H_{c+1} \text{-mod}$ and $S_c : U_c \text{-mod} \to U_{c+1} \text{-mod}$ are Morita equivalences.

Moreover, the idempotent functor $E_c : H_c \text{-mod} \to U_c \text{-mod}$ given by $M \mapsto eM$ is a Morita equivalence.

**Proof.** In order to prove that $S_c$ is an equivalence, we need to show that $Q = Q^{c+1}$ is a projective generator for $U_{c+1} \text{-mod}$, with endomorphism ring $\text{End}_{U_{c+1}}(Q) = U_c$. Arguing as in [EG, Theorem 1.5(iv)] the dual $Q^* = \text{Hom}_{U_{c+1}}(Q, U_{c+1})$ is $P = \delta^{-1}e - H_{c+1}e$. By the dual basis lemma, $Q$ is a projective $U_{c+1}$-module with $\text{End}_{U_{c+1}}(Q) = U_c$ if and only if $PQ = U_c$ while $Q$ is a generator if and only if $QP = U_{c+1}$. Substituting in the given formulae for $Q$ and $P$ shows that we need to prove that

$$H_{c+1}e - H_{c+1} = H_{c+1} \quad \text{and} \quad H_{c+1}e - H_{c+1} = H_{c+1} \quad \text{for } c \geq 0.$$  

Similarly, as $H_c e$ is a projective left $H_c$-module, $E_c$ will be a Morita equivalence if we prove that

$$H_c e H_c = H_c \quad \text{for } c \geq 0.$$  

Since $\tilde{S}_c = E_{c+1}^{-1} \circ S_c \circ E_c$, Equations 3.3.1 and 3.3.2 will suffice to prove the theorem.

The proof of Theorem 3.3 will be through a series of lemmas and we begin with the first equality in (3.3.1).

Set $d = c + 1$; thus $d \in \mathbb{R}_{\geq 1}$, with $d \notin \frac{1}{2} + \mathbb{Z}$.
3.4. Reduction to Category \( \mathcal{O} \). If \( H_d e \ldots H_d \) is a proper two-sided ideal of \( H_d \) it must be contained in a primitive ideal, and hence, by [Gi, Generalized Duflo Theorem], annihilate an object from category \( \mathcal{O}_d \). Thus it is enough to show that \( e_- \) does not annihilate any simple module belonging to \( \mathcal{O}_d \).

To do this we first show in Corollary 3.6 that the composition factors of \( \Delta_d(\mu) \) are of the form \( L_d(\lambda) \) for \( \lambda \leq \mu \). Under the \( \mathbb{Z} \)-strings ordering such a result is proved in [Gu] but as we work with the dominance ordering of partitions and representations, as defined in (2.6), this definitely requires work, see also (3.7).

We then show that the lowest weight copy of the sign module for \( W \) in \( \Delta_d(\mu) \) does not occur in any standard module \( \Delta_d(\lambda) \) for \( \lambda < \mu \). Since \( L_d(\mu) \) is the head (that is, the unique simple factor module) of \( \Delta_d(\mu) \) it will follow that \( e_- L_d(\mu) \neq 0 \).

3.5. Lemma. Let \( c \in \mathbb{R}_{\geq 0} \) with \( c \notin \frac{1}{2} + \mathbb{Z} \). If \( \text{Hom}_{H_c}(\Delta_c(\lambda), \Delta_c(\mu)) \neq 0 \) for \( \lambda, \mu \in \text{irrep}(W) \), then \( \lambda \leq \mu \) in the dominance ordering.

Proof. Let \( S_q = S_q(n, n) \) be the \( q \)-Schur algebra defined in [DJ2, Section 1], where \( q = \exp(2\pi i c) \). It is conjectured in [GGOR, Remark 5.17] that \( S_q \text{-mod} \) is equivalent to \( \mathcal{O}_c \). We cannot prove this, but we will show that there is a relationship which implies the lemma.

For each \( \mu \in \text{irrep}(W) \) there is an \( S_q \)-module \( W_q(\mu) \), called the \( q \)-Weyl module. By [DJ2, Corollary 8.6], there is an isomorphism

\[
(3.5.1) \quad \text{Hom}_{H_q}(S_q(\mu), S_q(\lambda)) \cong \text{Hom}_{S_q}(W_q(\lambda), W_q(\mu)).
\]

On the other hand, by (2.8.1) and (2.8.2) we have

\[
(3.5.2) \quad \text{Hom}_{H_c}(\Delta_c(\lambda), \Delta_c(\mu)) \cong \text{Hom}_{H_q}(S_q(\lambda)^*, S_q(\mu)^*) \cong \text{Hom}_{H_q}(S_q(\mu), S_q(\lambda)).
\]

Each \( W_q(\nu) \) has a simple head \( F_q(\nu) \), [DJ2, Theorem 4.6] and \( \{F_q(\nu) : \nu \in \text{irrep}(W)\} \) is a complete, repetition-free list of the simple \( S_q \)-modules up to isomorphism, [DJ2, Theorem 8.8]. Furthermore, \( F_q(\lambda) \) is a composition factor of \( W_q(\mu) \) only if \( \lambda \leq \mu \), [DJ2, Corollary 8.9]. By (3.5.1) and (3.5.2) a non-zero homomorphism \( \phi : \Delta_c(\lambda) \rightarrow \Delta_c(\mu) \) implies the existence of a non-zero homomorphism \( \phi' : W_q(\lambda) \rightarrow W_q(\mu) \). Thus \( F_q(\lambda) \) must be a composition factor of \( W_q(\mu) \) and so \( \lambda \leq \mu \).

3.6. Corollary. Assume that \( c \in \mathbb{R}_{\geq 0} \), with \( c \notin \frac{1}{2} + \mathbb{Z} \). If \( [\Delta_c(\mu) : L_c(\lambda)] \neq 0 \) for \( \lambda, \mu \in \text{irrep}(W) \), then \( \lambda \leq \mu \) in the dominance ordering.

Remarks. (1) For arbitrary \( c \) and \( \mu \), the unique occurrence of \( L_c(\mu) \) as a composition factor of \( \Delta_c(\mu) \) is as its head—see, for example, the discussion after Lemma 7 in [Gu, Section 2].

(2) Since \( \text{sign} \) is minimal in the dominance ordering, the lemma and the above remark imply that \( \Delta_c(\text{sign}) \) is irreducible for all \( c \in \mathbb{R}_{\geq 0} \). This can also be deduced from [Gu].

Proof. We argue by induction on \( \mu \). More precisely, suppose that \( [\Delta_c(\mu) : L_c(\lambda)] \neq 0 \) for some \( \mu \neq \lambda \) and that the lemma holds for any \( \nu < \mu \). (The induction starts since there are only finitely many \( \sigma \) with \( \sigma < \mu \).)
Let $P_c(\lambda)$ denote the projective cover of $\Delta_c(\lambda)$, as in [GGOR, Section 3.5], and write $K$ for the kernel of the associated homomorphism $\phi : P_c(\lambda) \to \Delta_c(\mu)$. By [Gu, Proposition 13] there is a $\Delta$-filtration of $P_c(\lambda)$

$$P_c(\nu) = M_0 \supset M_1 \supset \cdots \supset M_t = 0$$

with each factor $M_j/M_{j+1}$ of the form $\Delta_c(\lambda_j)$ for some $\lambda_j \in \text{irrep}(W)$. Thus there exists $i$ such that $M_i + K/K \neq 0$ but $M_{i+1} + K/K = 0$. This gives a non-zero composition

$$\psi : \Delta_c(\lambda_i) \cong M_i/M_{i+1} \to (M_i + K)/K \to P_c(\lambda)/K \to \Delta_c(\mu).$$

By Lemma 3.5, $\lambda_i \leq \mu$. If $\lambda_i = \mu$ then the first remark after the statement of the lemma would imply that $\psi$ and hence $\phi$ are surjective, contradicting the fact that $\lambda \neq \mu$. Thus $\lambda_i < \mu$. By BGG reciprocity [Gu, Theorem 19], $[P_c(\lambda) : \Delta_c(\lambda_i)] = [\Delta_c(\lambda_i) : L_c(\lambda)] \neq 0$ and so, by induction, $\lambda \leq \lambda_i$. Thus $\lambda < \mu$. □

3.7. A result analogous to Corollary 3.6 is proved as part of the proof of [Gu, Proposition 13]. However the $\mathbb{Z}$-strings ordering used in [Gu] is different from the dominance ordering. An explicit example where the orderings differ can be found when $n = 8$, by taking $\lambda = (6,1,1)$ and $\mu = (4,4)$. In this case $\lambda$ and $\mu$ are incomparable in the dominance ordering, but comparable in the $\mathbb{Z}$-strings ordering.

3.8. The canonical grading on $O_c$. The final ingredient we need for the proof of Theorem 3.3 is a canonical grading on $O_c$. Let $h_c \in H_c$ be defined as in (2.4.1). Then, for $M \in O_c$ and $\alpha \in \mathbb{C}$, set

$$W_\alpha(M) = \{m \in M : (h_c - \alpha)^k m = 0 \text{ for } k \gg 0\}.$$

By [GGOR, (2.4.1)] this gives the canonical grading $M = \sum_{\alpha \in \mathbb{C}} W_\alpha(M)$.

This observation has two useful consequences. First, if $\theta : M_1 \to M_2$ is an $H_c$-module homomorphism with $M_i \in O_c$, then $\theta(W_\alpha(M_1)) \subseteq W_\alpha(M_2)$ for each $\alpha \in \mathbb{C}$. Secondly, if $\rho \in H_c$ has $E$-deg $\rho = t$, then (2.4.2), implies that $\rho \cdot W_\alpha(M) \subseteq W_{\alpha+t}(M)$. Note that the standard module $\Delta_c(\mu)$ is therefore a lowest weight module since it is generated as a $\mathbb{C}[h]$-module by the space $1 \otimes \mu$.

3.9. To describe the graded structure of the standard modules we need a little notation. Recall that the space of coinvariants $\mathbb{C}[h]^{W \circ} = \mathbb{C}[h]/\mathbb{C}[h]^W \mathbb{C}[h]$ is a finite dimensional graded algebra isomorphic as a $W$-module to the regular representation. As in [Op], the polynomials

$$(3.9.1) \quad f_\mu(v) = \sum_{i \geq 0} [\mathbb{C}[h]^{W \circ} : \mu] v^i$$

are called the fake degrees of $\mu \in \text{irrep}(W)$. We define $n(\mu)$ to be the lowest power of $v$ appearing in $f_\mu(v)$; thus, $f_\mu(v) = av^{n(\mu)} + \text{higher order terms}$. In the notation of [Ha3], $n(\mu)$ is equal to the partition statistic $\sum_i \mu_i(i-1)$ (see the proof of [Go1, Theorem 6.4]). Finally, (3.9.1) implies that

$$(3.9.2) \quad f_\mu(1) = \dim \mu^t = \dim \mu = f_\mu(1) \quad \text{for } \mu \in \text{irrep}(W).$$
3.10. Given a graded $W$-module $M = \sum_{\alpha \in \mathbb{C}} W_\alpha (M)$ we define its graded Poincaré series to be

$$p(M, v, W) = \sum_{\alpha \in \mathbb{C}} v^\alpha \sum_{\lambda \in \text{Irrep}(W)} [W_\alpha (M) : \lambda][\lambda].$$

This is easily determined for standard modules.

**Proposition.** (1) Under the canonical grading, the subspace $1 \otimes \mu$ of $\Delta_c(\mu)$ has weight $m + c(n(\mu) - n(\mu^t))$, where $m = (n - 1)/2$.

(2) The Poincaré series of $\Delta_c(\mu)$ as a graded $W$-module is

$$p(\Delta_c(\mu), v, W) = v^{m+c(n(\mu)-n(\mu^t))} \frac{\sum_{\lambda} f_\lambda(v)[\lambda \otimes \mu]}{\prod_{i=2}^n (1 - v^i)}.$$  

**Proof.** (1) We need to compute the action of $h = \frac{1}{2} \sum_{i=1}^{n-1} (x_iy_i + y_ix_i)$ on the space $1 \otimes \mu$. By the defining relations of $H_c$ from (2.1), and the fact that the $\{x_i\}$ and $\{y_i\}$ are dual bases, we obtain

$$h = \sum_i x_iy_i + (n - 1)/2 - \frac{1}{2} \sum_{s \in S} c_s(y_i)x_i(\alpha^s_i)^s = \sum_i x_iy_i + (n - 1)/2 - \frac{1}{2} \sum_{s \in S} c_s(\alpha^s_i)s = \sum_i x_iy_i + m - c \sum_{s \in S} s.$$ 

The action of $\sum (1 - s)$ on $\lambda \in \text{Irrep}(W)$ can be derived from [BM, Lu]. More precisely, $\lambda$ is special by [Lu, (4.2.2)] and so $\lambda(\lambda) = b_\lambda = a_\lambda$ in the notation of [Lu]. Therefore, by [BM, Section 4.21] and [Lu, Section 4.1 and (5.11.5)], $\sum (1 - s)$ acts on $1 \otimes \mu$ with weight $N + n(\lambda) - n(\lambda^t)$, where $N = n(n - 1)/2$ is the cardinality of $S$. Thus $\sum s$ acts on $1 \otimes \mu$ with weight $-(n(\mu) - n(\mu^t))$ and hence $h$ acts with weight $m + c(n(\mu) - n(\mu^t))$.

(2) As graded $W$-modules, $\Delta(\mu) \cong (\mathbb{C}[h] \otimes \mu)[k]$ for $k = m + c(n(\mu) - n(\mu^t))$. The shift arises from the fact that, by (1), the generator $1 \otimes \mu$ of $\Delta_c(\mu)$ lives in degree $k$. The Chevalley-Shephard-Todd Theorem implies that, as graded $W$-modules, $\mathbb{C}[h] \cong \mathbb{C}[h]^W \otimes \mathbb{C}[h]^{\text{co}W}$. Now $\mathbb{C}[h]^W$ is a polynomial ring with generators in degrees $2 \leq i \leq n$ and so its Poincaré polynomial is $\prod_{i=2}^n (1 - v^i)^{-1}$. On the other hand, the coinvariant ring $\mathbb{C}[h]^{\text{co}W}$ has graded Poincaré polynomial $\sum_{\lambda} \sum_i [\mathbb{C}[h]^{\text{co}W} : \lambda][\lambda]v^i$. By definition, this is just $\sum_{\lambda} f_\lambda(v)[\lambda]$. Combining these observations gives (3.10.1). \hfill \square

3.11. **Completion of the proof of Theorem 3.3.** We first prove that $H_{d-1}H_d = H_d$ (where $d = c + 1$, as before). Since $\mu \cong \mu^*$ for symmetric groups, the sign representation is a direct summand of $\mu \otimes \nu$ if and only if $\nu = \mu^t$. Thus (3.10.1) implies that sign first appears in $\Delta_d(\mu)$ in the weight space

$$m + d(n(\mu) - n(\mu^t)) + n(\mu^t) = m + dn(\mu) - (d - 1)n(\mu^t) \quad \text{where} \quad m = (n - 1)/2.$$

If $\lambda \leq \mu$ then $n(\lambda) \geq n(\mu)$ by [Sh, Theorem B and Proposition 1.6]. Moreover, as $\lambda^t \leq \mu^t$, we have $n(\lambda^t) \leq n(\mu^t)$. Since $d \in \mathbb{R}_{\geq 1}$,

$$m + dn(\lambda) - (d - 1)n(\lambda^t) \geq m + dn(\mu) - (d - 1)n(\mu^t)$$

with equality if and only if $\lambda = \mu$. 

13
It follows that the copy of \( \text{sign} \) appearing in the lowest possible weight space of \( \Delta_d(\mu) \) is never a weight of \( \Delta_d(\lambda) \) for \( \lambda < \mu \). By Corollary 3.6, this means that this copy of \( \text{sign} \) is a weight for \( L_d(\mu) \) and hence that \( e.L_d(\mu) \neq 0 \). By (3.4) this implies that \( H_d e \cdot H_d = H_d \), and so the first equality of (3.3.1) is proven.

It remains to show that \( H_c e H_c = H_c \) for \( c \in \mathbb{R}_{\geq 0} \). The argument of (3.4) shows that we need to prove that \( e \) does not annihilate any simple module from \( O_c \). In this case \( \text{triv} \) appears in \( \mu \otimes \nu \) if and only if \( \nu = \mu \). Therefore, (3.10.1) now implies that \( \text{triv} \) first appears in \( \Delta_c(\mu) \) in degree \( m + c(n(\mu) - n(\mu^t)) + n(\mu) \). Let \( \lambda \leq \mu \). Then

\[
m + c(n(\lambda) - n(\lambda^t)) + n(\lambda) = m + (c+1)n(\lambda) - cn(\lambda^t) \geq m + c(n(\mu) - n(\mu^t)) + n(\mu),
\]

with equality if and only if \( \lambda = \mu \). This means that \( \text{triv} \) appears in \( \Delta_c(\lambda) \) in a higher degree than its first appearance in \( \Delta_c(\mu) \). In particular, the simple quotient \( L_c(\mu) \) of \( \Delta_c(\mu) \) contains a copy of \( \text{triv} \) and so it cannot be annihilated by \( e \). This therefore completes the proof of (3.3.1) and (3.3.2) and hence proves the theorem.

\[ \square \]

3.12. General equivalences. We now give the promised extension of Theorem 3.3 to more general values of \( c \). Since it requires no extra work, and it is put to crucial use in [BFG], we will also prove the result over more general base fields. Thus if \( k \) is a subfield of \( \mathbb{C} \), with \( c \in k \), let \( H(k)_c \) denote the \( k \)-algebra defined by the generators and relations from (2.1). We write \( U(k)_c \), \( Q(k)_c^{c+1} \), etc, for the corresponding objects defined over \( k \).

**Hypothesis.** Set \( \mathcal{C} = \{ z : z = \frac{m}{d} \text{ where } m, d \in \mathbb{Z} \text{ with } 2 \leq d \leq n \text{ and } z \notin \mathbb{Z} \} \). Assume that \( c \in \mathbb{C} \) is such that \( c \notin \frac{1}{2} + \mathbb{Z} \). If \( c \) is a rational number with \( -1 < c < 0 \) assume further that \( c \notin \mathcal{C} \).

3.13. **Corollary.** Let \( k \subseteq \mathbb{C} \) be a field and assume that \( c \in k \) satisfies Hypothesis 3.12.

(1) \( U(k)_c \) and \( H(k)_c \) are Morita equivalent. If \( c \notin (-2,-1)_c = \{ z \in \mathbb{C} : -2 < z < 0 \} \), then \( U(k)_c \) is Morita equivalent to \( U(k+c+1)_c \).

(2) Let \( a = -c \). Then \( H(k)_a \) is Morita equivalent to \( U(k)_a = e.H(k)_a e. \) If \( a \notin (1,2)_c \), then \( U(k)_a \) is Morita equivalent to \( U(k-1+c)_a \).

**Proof.** (1) We start with the case \( U_c = U(\mathbb{C})_c \). If \( c \notin \mathcal{C} \) then it follows from [BEG1, Theorem 8.1] and [DJ1, Theorem 4.3] that \( H_c, U_c \) and \( U_c^- \) are simple, Morita equivalent rings (see the introduction to [BEG3] for the details). Since this also applies to \( H_{c+1} \) the conditions (3.3.1) are trivially satisfied and the result follows.

Thus we may assume that \( c \in \mathcal{C} \). If \( c \geq -1 \), then necessarily \( c \geq 0 \) and so the result follows from Proposition 3.3. Otherwise \( c \leq -1 \). In this case the discussion before [De, Remark 2.2] shows that there is an isomorphism \( \chi : H_c \rightarrow H_{-c} \) satisfying \( \chi(e_-) = e \). Thus, for any \( c \), (3.2.1) implies that \( U_c \cong U_c^- \cong eH_{-c-1}e = U_{-c-1} \). The result for \( c \leq -1 \) therefore follows from the cases already discussed.

Finally, let \( k \) be an arbitrary subfield of \( \mathbb{C} \) and consider \( U(k)_c \). In order to prove, for example, that \( U(k)_c \) is Morita equivalent to \( U(k)_{c+1} \) we need to prove that \( Q(k)P(k) = U(k)_{c+1} \) and \( P(k)Q(k) = U(k)_c \). By
construction, \( Q(\mathbb{C}) = Q(k) \otimes_k \mathbb{C} \), and similarly for \( P(\mathbb{C}) \). By the earlier part of the proof, \( U(\mathbb{C})_c/P(\mathbb{C})Q(\mathbb{C}) = 0 \). The faithful flatness of \( U(\mathbb{C})_c = U(k)_c \otimes_k \mathbb{C} \) as a \( U(k)_c \)-module then ensures that \( U(k)_c/P(k)Q(k) = 0 \), whence \( PQ = 0 \). All the other steps in the proof follow in exactly the same way.

(2) Using the identity \( U_c \cong U_{-c} \), this follows from part (1). \( \square \)

3.14. **Remarks.** (1) The condition that \( c \notin \frac{1}{2} + \mathbb{Z} \) is needed in Theorem 3.3 and Corollary 3.13 in order to apply (2.8.2) and may be unnecessary. This is the case when \( n = 2 \) as \( U_c \) is Morita equivalent to \( U_{c+1} \) if and only if \( c \neq -\frac{3}{2}, -\frac{1}{2} \) (see, for example, [EG, Proposition 8.2]). The point about the excluded cases is that \( U_{-\frac{3}{2}} \) is simple but the two neighbouring algebras, \( U_{\frac{1}{2}}, U_{-\frac{1}{2}} \) are not. Combining [EG, Proposition 8.2] with [St, Theorem B] shows that \( U_{-\frac{1}{2}} \) has infinite global dimension, and so the next Corollary 3.15 also fails for this value of \( c \).

(2) This also shows that the hypothesis \( c \notin (-2,0)_c \) is serious. Indeed, for any \( n \geq 2 \), let \( c = -m/n \in (-1,0). \) Then one can prove that the factor module \( V_c = \Delta_c(\text{sign})/I_c \) considered in [CE, Theorem 3.2] does not contain a copy of the \( W \)-module \( \text{triv} \) (we thank Pavel Etingof for this fact). In particular \( cV_c = 0 \) and so the functor \( E_c \) is not an equivalence. If we further assume that \( (m,n) = 1 \), then \( V_c \) is the unique irreducible finite dimensional \( H_c \)-module by [CE, Corollary 3.3] and [BEG2, Theorem 1.2(ii)]. Since \( U_c = \text{End}_{H_c}(cH_c) \), this implies that \( U_c \) has no finite dimensional modules. However, by Corollary 3.13(1) and [BEG2, Theorem 1.2] \( U_{c+1} \)-mod does have such modules and so there is no equivalence between \( U_c \) and \( U_{c+1} \).

3.15. **Corollary.** Assume that \( c \in \mathbb{C} \) satisfies Hypothesis 3.12. Then \( H_c \) and \( U_c \) have finite homological global dimension and satisfy the Auslander-Gorenstein conditions and Cohen-Macaulay conditions of [Le].

**Proof.** Since this result takes us a little far afield, the details of the proof are left to the interested reader. Standard techniques show that \( \text{ogr} H_c \cong \mathbb{C}[\mathfrak{h} \oplus \mathfrak{h}^*] \ast W \) and hence \( H_c \) have the given properties (see, for example, [Br, Theorem 4.4]). By Corollary 3.13, \( U_c \) is Morita equivalent to \( H_c \) and it follows that \( U_c \) also has these properties. \( \square \)

3.16. **The shift functor on \( \mathcal{O}_c \).** Many computations for \( U_c \) reduce to computations in category \( \mathcal{O} \) and so it is important to know that, under the hypotheses of Theorem 3.3, \( S_c \) does provide an equivalence between the corresponding categories. This is the point of the next result.

**Proposition.** Assume that \( c \in \mathbb{C} \) satisfies Hypothesis 3.12 and that \( c \notin Q_{\leq -1} \). Then the shift functor \( S_c \) restricts to an equivalence between \( \mathcal{O}_c \) and \( \mathcal{O}_{c+1} \) such that \( S_c(\Delta_c(\lambda)) \cong \Delta_{c+1}(\lambda) \) for all partitions \( \lambda \) of \( n \). Thus \( S_c(e\Delta_c(\lambda)) = e\Delta_{c+1}(\lambda) \).

**Remark.** By Corollary 3.13(2), an analogue of the proposition also holds when \( c \in Q_{\leq -1} \), provided that one shifts in a negative direction.

**Proof.** The final assertion of the proposition is immediate from the previous one combined with Corollary 3.13(1).
We begin by showing that $\widetilde{S}_c$ restricts to an equivalence between $O_c$ and $O_{c+1}$. Fix $M \in O_c$. Let $I_t = \mathbb{C}[h^+]^W_{\geq t}$ denote the $W$-invariant elements of $\mathbb{C}[h^+]$ of degree at least $t$ and set $I_t = I_t/\mathbb{C}[h^+]$, Then $\mathbb{C}[h^+]/I_t$ is a finite dimensional algebra and so all homogeneous elements of $\mathbb{C}[h^+]$ of large degree belong to $I_t$. Thus it is enough to show that, if $\widetilde{m} = he_{-\delta} \otimes em \in \widetilde{S}_c(M) = H_{c+1}e_{-\delta} \otimes U_c eM$, for some $h \in H_{c+1}$ and $m \in M$, then $\widetilde{m}$ is annihilated by $I_t$ for $t \gg 0$.

Recall the $E$-grading on $H_c$ from (2.4). Since $\mathbb{C}[h^+]$ acts locally nilpotently on $M$, the PBW isomorphism (2.2.1) shows that any homogeneous element of $H_c$ of sufficiently large negative $E$-degree annihilates $m \in M$. Thus, assume that $qm = 0$ for all $q \in H_c$ with $E$-deg$(q) \leq -t$ and let $p \in \mathbb{C}[h^+]^W_{\geq t}$. Then

$$phe_{-\delta} \otimes em = [p,h]e_{-\delta} \otimes em + h\delta^{-1}pe_{-\delta} \otimes em = [p,h]e_{-\delta} \otimes em + he_{-\delta} \otimes \delta^{-1}pde_{\delta}em.$$  

Since $E$-deg$\delta^{-1}p\delta = E$-deg$p \leq -t$, we have $\delta^{-1}p\delta em = 0$ by the hypothesis on $t$.

Therefore $p(he_{-\delta} \otimes em) = [p,h]e_{-\delta} \otimes em$ for any such $p$. Since the choice of $t$ was independent of $h$, this implies that $p'(he_{-\delta} \otimes em) = ad(p'h)(e_{-\delta} \otimes em)$, for any $r > 0$. Now, $p$ commutes with both $\mathbb{C}[W]$ and $\mathbb{C}[h^+]$, and so the defining relations of $H_{c+1}$ from (2.1) ensure that the adjoint action of $p \in \mathbb{C}[h^+]^W$ on $H_{c+1}$ is locally nilpotent (see also [BEG1, Lemma 3.3(v)]). Therefore a sufficiently large power of $p$ annihilates $he_{-\delta} \otimes em$. Thus $\widetilde{S}_c(M) \in O_{c+1}$ and $\widetilde{S}_c$ does restrict to the desired equivalence.

It remains to compute $\widetilde{S}_c(\Delta_c(\lambda))$ and we begin with the analogous problem on $H_{c+1}^\text{reg}$. In the notation of (2.3.2),

$$\widetilde{S}_c(\Delta_c(\lambda))^{\text{reg}} = H_{c+1}^\text{reg}e_{-\delta} \otimes_{U_{c+1}^{\text{reg}}} e\Delta_c(\lambda).$$

By (2.3.2), $H_{c+1}^\text{reg} \cong A = D(\mathbb{C}^\text{reg}) * W$ and so $\widetilde{S}_c(\Delta_c(\lambda))^{\text{reg}} \cong Ae_{-\delta} \otimes_B e\Delta_c(\lambda)^{\text{reg}}$, where $B = \delta^{-1}e_{-A}e_{-\delta}$. On the other hand, (2.3.1) induces an isomorphism

$$\theta : Ae_{-\delta} \otimes_B e\Delta_c(\lambda)^{\text{reg}} \rightarrow Ae \otimes_{eAe} e\Delta_c(\lambda)^{\text{reg}}; \quad ae_{-\delta} \otimes em \mapsto a\delta e \otimes em.$$  

Combined with the identity $He_{-A}eH_c = H_c$ from Corollary 3.13(1), this implies that

(3.16.1) $$\widetilde{S}_c(\Delta_c(\lambda))^{\text{reg}} \cong Ae \otimes_{eAe} e\Delta_c(\lambda)^{\text{reg}} \cong (H_c e \otimes_{U_c} e\Delta_c(\lambda))^{\text{reg}} \cong \Delta_c(\lambda)^{\text{reg}} \neq 0.$$  

If $c \not\in C$, we are done. Indeed, in this case [BEG1, Corollary 2.11] implies that $\Delta_{c+1}(\lambda)$, $\Delta_c(\lambda)$ and hence $\widetilde{S}_c(\Delta_c(\lambda))$ are all simple modules. The isomorphism (3.16.1) implies that $\widetilde{S}_c(\Delta_c(\lambda)) \hookrightarrow \Delta_{c+1}(\lambda)^{\text{reg}}$. Under this embedding, $\widetilde{S}_c(\Delta_c(\lambda)) \cap \Delta_{c+1}(\lambda) \neq 0$ and hence $\widetilde{S}_c(\Delta_c(\lambda)) = \Delta_{c+1}(\lambda)$.

We may therefore assume that $c \in C$, in which case Hypothesis 3.12 implies that $c \geq 0$ and we can use the KZ-functor from (2.8). By (3.16.1) and (2.8.1), $KZ(\widetilde{S}_c(\Delta_c(\lambda))) \cong KZ(\Delta_c(\lambda)) \cong Spq(\lambda)^*$. By (2.8.2) and (3.5.1) we therefore have

(3.16.2) $$\text{Hom}_{H_{c+1}}(\widetilde{S}_c(\Delta_c(\lambda)), \Delta_{c+1}(\lambda)) \cong \text{Hom}_{Spq}(Spq(W_q(\lambda), W_q(\lambda))) = \mathbb{C}.$$  

It follows from Corollary 3.6 that the composition factors of $\Delta_{c+1}(\lambda)$ are of the form $L_{c+1}(\nu)$ with $\nu \leq \lambda$ in the dominance ordering. We will show by an ascending induction on this ordering that $\widetilde{S}_c(\Delta_c(\lambda)) \cong \Delta_{c+1}(\lambda)$. 


If \( \lambda \) is minimal in the dominance ordering then \( \lambda = \text{sign} \) and so both \( \Delta_{c+1}(\lambda) \) and \( \tilde{S}_c(\Delta_c(\lambda)) \) are simple by Remark 3.6. By (3.16.2) there is a non-zero map from \( \tilde{S}_c(\Delta_c(\lambda)) \) to \( \Delta_{c+1}(\lambda) \) which therefore must be an isomorphism. This begins the induction.

Let \( \lambda \) be arbitrary and suppose that, for all \( \nu < \lambda \) in the dominance ordering, we have \( \tilde{S}_c(\Delta_c(\nu)) \cong \Delta_{c+1}(\nu) \), and hence that \( \tilde{S}_c(L_c(\nu)) \cong L_{c+1}(\nu) \). Since \( \tilde{S}_c \) is an equivalence, \( \tilde{S}_c(\Delta_c(\mu)) \) has simple head \( \tilde{S}_c(L_c(\mu)) \) for each \( \mu \). By (3.16.2) \( \tilde{S}_c(L_c(\lambda)) \) is therefore isomorphic to a composition factor of \( \Delta_{c+1}(\lambda) \). But, by Corollary 3.6 and the remark thereafter, the composition factors of \( \Delta_{c+1}(\lambda) \), except for the head, are of the form \( L_{c+1}(\nu) \) for \( \nu < \lambda \). Thus the non-zero map (3.16.2) must send the head of \( \tilde{S}_c(\Delta_c(\lambda)) \) to the head of \( \Delta_{c+1}(\lambda) \) and so induce an isomorphism \( \tilde{S}_c(\Delta_c(\lambda)) \xrightarrow{\sim} \Delta_{c+1}(\lambda) \). This completes the inductive step, and hence the proof of the proposition.

\[\square\]

4. The Hilbert scheme

4.1. Haiman’s work on Hilbert schemes gives detailed information about their structure, in particular as “Proj” of appropriate Rees rings. The resulting formulae for the Poincaré series of these rings will be crucial to the proof of the main theorem in Section 6. In this section, we briefly describe the relevant results from the literature and use this to derive the appropriate Poincaré series.

4.2. Let \( \text{Hilb}^n\mathbb{C}^2 \) be the Hilbert scheme of \( n \) points on the plane, which we realise as the set of ideals of colength \( n \) in the polynomial ring \( \mathbb{C}[\mathbb{C}^2] \). Similarly, identify the variety \( S^n\mathbb{C}^2 \) of unordered \( n \)-tuples of points in \( \mathbb{C}^2 \) with the categorical quotient \( \mathbb{C}^{2n}/W \) under the diagonal action of \( W \) on \( \mathbb{C}[\mathbb{C}^{2n}] \). Then the map \( \tau : \text{Hilb}^n\mathbb{C}^2 \to S^n\mathbb{C}^2 = \mathbb{C}^{2n}/W \) which sends an ideal to its support (counted with multiplicity) is a resolution of singularities (see, for example, [Na, Theorem 1.15]).

We will actually be interested in a resolution of singularities for \( \mathbb{C}[\mathfrak{h} \oplus \mathfrak{h}^*]^W \) rather than \( \mathbb{C}[\mathbb{C}^{2n}]^W \), simply because the associated graded ring of \( U_c \) is \( \mathbb{C}[\mathfrak{h} \oplus \mathfrak{h}^*]^W \). The results we need follow easily from the corresponding results on \( \text{Hilb}^n\mathbb{C}^2 \) and so we begin with the latter.

4.3. The (isospectral) Hilbert scheme. Following [Ha3, Definition 3.2.4] the isospectral Hilbert scheme \( X_n \) is the reduced fibre product

\[ X_n \xrightarrow{f_1} \mathbb{C}^{2n} \]
\[ \rho_1 \downarrow \hspace{1cm} \downarrow \]
\[ \text{Hilb}^n\mathbb{C}^2 \xrightarrow{\tau} \mathbb{C}^{2n}/W. \]

It is a highly non-trivial fact (see [Ha3, Theorem 3.1 and the proof of Proposition 3.7.4]) that \( \rho_1 \) is a flat map of degree \( n \).

Haiman has given a description of both \( \text{Hilb}^n\mathbb{C}^2 \) and \( X_n \) as Proj of appropriate graded rings and we recall this description since it will be extremely important to us. Let \( A^1 = \mathbb{C}[\mathbb{C}^{2n}]^c \) be the space of \( W \)-alternating polynomials in \( \mathbb{C}[\mathbb{C}^{2n}] \) and write \( J^1 = \mathbb{C}[\mathbb{C}^{2n}]A^1 \) for the ideal generated by \( A^1 \). For \( d \geq 1 \) define \( A^d \) and \( J^d \).
to be the respective $d^{th}$ powers of $A^1$ and $J^1$ using multiplication in $\mathbb{C}[\mathbb{C}^{2n}]$; thus $J^d = \mathbb{C}[\mathbb{C}^{2n}]A^d$. Finally, set $J^0 = \mathbb{C}[\mathbb{C}^{2n}]$, $A^0 = \mathbb{C}[\mathbb{C}^{2n}]W$ and $A = \bigoplus_{d \geq 0} A^d \cong A^0[\epsilon A^1]$. Then [Ha1, Proposition 2.6] proves that

\begin{equation}
(4.3.1) \quad \text{Hilb}^n\mathbb{C}^2 \cong \text{Proj } \mathbb{A} \text{ as a scheme over Spec } A^0 = \mathbb{C}^{2n}/W
\end{equation}

Similarly, $X_n \cong \text{Proj } S$, where $S = \mathbb{C}[\mathbb{C}^{2n}][tJ^1]$, is the blowup of $\mathbb{C}^{2n}$ at $J^1$ [Ha3, Proposition 3.4.2].

4.4. Observe that $J^d$ is generated by its $W$-alternating or $W$-invariant elements, respectively, depending on whether $d$ is odd or even. Following Haiman we refer to these elements as having correct parity.

**Lemma.** (1) For any $d \geq 0$, $\mathbb{A}^d$ consists of the elements of the $J^d$ with the correct parity.

(2) If $\mathbb{C}^n$ denotes the first copy of that space in $\mathbb{C}^{2n}$, then $J^d$ is a free module over both $\mathbb{C}[\mathbb{C}^n]$ and $\mathbb{C}[\mathbb{C}^n]W$.

**Proof.** (1) The statement is clearly true for $d = 0, 1$. Assume, by induction, that it is true for $d - 1$. We will suppose that $d$ is even, the argument in the odd case being similar. Since $A^1$ generates the ideal $J^1$, any element $x \in J^d$ can be decomposed as $x = \sum p_iq_i$ where $p_i \in J^{d-1}$ and $q_i \in A^1$. Since $q_i e = e_q q_i$ for all $i$, if $x$ has the correct parity then $x = xe = \sum_i (p_iq_i) e = \sum_i (p_i e_q q_i)$. But $J^{d-1}e_q$ is the subset of $W$-alternating elements of $J^{d-1}$ and so $J^{d-1}e_q = \mathbb{A}^{d-1}$ by induction. Thus $x \in \mathbb{A}^{d-1}A^1 = \mathbb{A}^d$.

(2) By [Ha3, Proposition 4.11.1] $J^d$ is a projective module over $\mathbb{C}[\mathbb{C}^n]$ and hence over $\mathbb{C}[\mathbb{C}^n]W$. Since $\mathbb{C}[\mathbb{C}^n]$ and $\mathbb{C}[\mathbb{C}^n]W$ are polynomial rings, any such projective module is free by the Quillen-Suslin Theorem. \(\square\)

4.5. **Geometric interpretation.** There is a geometric description of both $\mathbb{A}^d$ and $J^d$. Let $B_1$ be the tautological rank $n$ vector bundle on Hilb$^n\mathbb{C}^2$ and let $P_1 = (\rho_1)_* O_{X_n}$ denote the Procesi bundle of rank $n!$ arising from the map $\rho_1 : X_n \to \text{Hilb}^n\mathbb{C}^2$. Write $L_1 = \bigwedge^n B_1$ for the determinant bundle of $B_1$. By [Ha1, Proposition 2.12] $L_1$ is also the canonical ample line bundle $O_{\text{Hilb}^n\mathbb{C}^2}(1)$ associated to the presentation $\text{Hilb}^n\mathbb{C}^2 \cong \text{Proj } \mathbb{A}$.

4.6. Set $l = dn$ for some $d \geq 1$ and write $R(n, l) = H^0(\text{Hilb}^n\mathbb{C}^2, P_1 \otimes B_1)$. One should note that $R(n, l)$ is defined in [Ha4] to be the coordinate ring of the polygraph $Z(n, l)$ but, by [Ha4, Theorem 2.1], it is also isomorphic to the given ring of global sections. There is an action of $W \times W^d$ on $P_1 \otimes B_1^l$, with $W$ acting fibrewise on $P_1$ and $W^d \subset S_l$ acting on $B_1^l$ by permutations. By construction, $(P_1)^W = O_{\text{Hilb}^n\mathbb{C}^2}$ and $(B_1^l)^{\epsilon} = L_1^{l-1}$, where $\epsilon$ denotes the sign representation of $W^d$.

The proof of [Ha3, Proposition 4.11.1] shows that $J^d \cong R(n, l)^{\epsilon d}$. On the other hand, the action of $W^d$ is trivial on $\text{Hilb}^n\mathbb{C}^2$, so $P_1 \otimes B_1^l$ is a direct sum of its isotypic components. Hence

\begin{equation}
(4.6.1) \quad J^d \cong \bigwedge(n, l)^{\epsilon d} = H^0(\text{Hilb}^n\mathbb{C}^2, (P_1 \otimes L_1)^{\epsilon d}) = H^0(\text{Hilb}^n\mathbb{C}^2, P_1 \otimes L_1^d).
\end{equation}

It is not true, however, that the natural $W$-action on the two sides agrees. Indeed, thanks to the proof of [Ha2, Proposition 4.2] the isomorphism written $W$-equivariantly is

\begin{equation}
(4.6.2) \quad J^d \otimes e^{\otimes d} \cong H^0(\text{Hilb}^n\mathbb{C}^2, P_1 \otimes L_1^d).
\end{equation}
The reason for this is that the isomorphism in (4.6.1) is given by the \( \mathbb{C}[\mathbb{C}^2] \)-module homomorphism sending (in the notation of [Ha2]) the generators \( \Delta_i(a, b) \cdots \Delta_i(a, b) \) on the right hand side to their evaluations on the left hand side: \( a \mapsto x, b \mapsto y \). The element \( \Delta_i(a, b) \) has a trivial \( W \)-action as no \( x \)'s or \( y \)'s are involved, whereas its specialisation has a \( W \)-action of \( c^{\otimes d} \) since that specialisation is the product of \( d \) determinants.

As a result, (4.6.2) and Lemma 4.4 combine to prove:

Lemma. There is an isomorphism of \( \mathbb{A}^0 \)-modules \( \mathbb{A}^d \cong \mathbb{R}(n, l)^{W \times c_d} = H^0(\text{Hilb}^n \mathbb{C}^2, \mathcal{L}^d) \).

4.7. (Bi)graded characters. There is a bigrading on \( \mathbb{C}[\mathbb{C}^2] = \mathbb{C}[x, y] \) with deg \( x_i = (1, 0) \) and deg \( y_j = (0, 1) \) which, as in [Ha4, (12)], arises from the action of \( \mathbb{T}^2 = \mathbb{(C^*)^2} \) on the plane \( \mathbb{C}^2 \) given by \( (\alpha, \beta) \cdot (u, v) = (\alpha^{-1} u, \beta^{-1} v) \) for \( (u, v) \in \mathbb{C}^2 \). This action extends to \( \text{Hilb}^n \mathbb{C}^2 \), and the bundles \( \mathcal{P}_1, \mathcal{B}_1, \mathcal{L}_1 \) are naturally \( \mathbb{T}^2 \)-equivariant. The isomorphisms from (4.6.1) and Lemma 4.6 respect the induced bigradings. Of course, the sections \( M \) of any one of these modules obtains an induced action of \( \mathbb{T}^2 \) and this is equivalent to a \( \mathbb{Z}^2 \)-grading \( M = \bigoplus M_{i, j} \); explicitly, an element \( f \in M \) is homogeneous of weight \((i, j)\) if \((\alpha, \beta)f = \alpha^i \beta^j f \).

The \( \mathbb{T}^2 \)-fixed points of \( \text{Hilb}^n \mathbb{C}^2 \) are precisely the ideals \( I_{\mu} \) that are associated to partitions \( \mu \) of \( n \) by

\[
I_{\mu} = \mathbb{C} \cdot \{x^r y^s : (r, s) \notin d(\mu)\} \subseteq \mathbb{C}[x, y],
\]

see [Ha4, Proposition 3.1]. The set of monomials \( \mathcal{B}_{\mu} = \{x^r y^s : (r, s) \in d(\mu)\} \) that are not in \( I_{\mu} \) form a natural \( \mathbb{C} \)-basis of \( \mathbb{C}[x, y]/I_{\mu} \).

4.8. For a bigraded space \( V = \sum_{i, j} V_{i, j} \) with finite dimensional weight spaces we define the bigraded Poincaré series of \( V \) to be

\[
p(V, s, t) = \sum_{i, j} \dim(V_{i, j}) s^i t^j.
\]

Haiman has calculated the bigraded Poincaré series of \( \mathbb{R}(n, l) \) and a similar calculation will allow us to find the bigraded Poincaré series of \( \mathbb{J}^d \). For a pair of partitions \( \lambda, \mu \) let \( K_{\lambda \mu}(t, s) \) be the Kostka–Macdonald coefficients defined in [Mac, VI, (8.11)]. Set

\[
\Omega(\mu) = \prod_{x \in d(\mu)} (1 - s^{1+l(x)} t^{-a(x)}) (1 - s^{-l(x)} t^{1+a(x)}) \quad \text{and} \quad P_{\mu}(s, t) = \sum_{\lambda} s^{n(\mu)} K_{\lambda \mu}(t, s^{-1}) f_{\lambda}(1).
\]

We remark that many of the formulæ we cite from Haiman’s papers are given in terms of Frobenius series \( \mathcal{F}_M(z; s, t) \) but, as in [Ha2, (6.5)], we can always specialise these to Hilbert series \( p(M, s, t) \) by specialising \( s_{\lambda}(z) \) to \( f_{\lambda}(1) = \dim \lambda \).

**Proposition.** Under the \( \mathbb{T}^2 \)-bigraded structure, the bigraded Poincaré series of \( \mathbb{J}^d \) is

\[
p(\mathbb{J}^d, s, t) = \sum_{\mu} P_{\mu}(s, t) \Omega(\mu)^{-1} s^{d(\mu)} t^{d(\mu)}.
\]
Proof. By [Ha4, Theorem 2.1] \( H^i(\text{Hilb}^n \mathbb{C}^2; P_1 \otimes L_i^1) = 0 \) for \( i > 0 \), while \( H^0(\text{Hilb}^n \mathbb{C}^2; P_1 \otimes L_i^1) = \mathbb{J}^d \) by (4.6.1). Thus, in the notation of [Ha4, Section 3], \( p(\mathbb{J}^d, s, t) = \chi_{P_1 \otimes L_i^1}(s, t) \) and so, by [Ha4, Proposition 3.2],

\begin{equation}
(4.8.1) \quad p(\mathbb{J}^d, s, t) = \sum_{\mu} p(P_1 \otimes L_i^1(I_\mu), s, t) \Omega(\mu)^{-1} = \sum_{\mu} p(P_1(I_\mu), s, t)p(L_1(I_\mu), s, t)^d \Omega(\mu)^{-1}.
\end{equation}

Here we have used the fact that, as \( I_\mu \) defines a finite dimensional scheme, we can identify the sheaf \( P_1 \otimes L_i^1(I_\mu) \) with its global sections, and so \( p(P_1 \otimes L_i^1(I_\mu), s, t) \) is naturally defined.

We now evaluate the right hand side of (4.8.1). It is proved in [Ha1, (3.9)], using the notation of [Ha1, (1.9)], that \( p(L_1(I_\mu), s, t) = \prod_{x \in d(\mu)} s^{l(x)} L(x) = s^{n(\mu)} t^{n(\mu)} \). On the other hand, by [Ha4, Proposition 3.4] (which is proved in [Ha3, Section 3.9] and uses the notation of [Ha4, (46)]), \( p(P_1(I_\mu), s, t) = P_\mu(s, t) \). Substituting these observations into (4.8.1) shows that

\[ p(\mathbb{J}^d, s, t) = \sum_{\mu} P_\mu(s, t) \Omega(\mu)^{-1} s^{dn(\mu)} t^{dn(\mu)}, \]

as required. \( \square \)

4.9. **Blowing up** \( (\mathfrak{h} \oplus \mathfrak{h}^*)/W \). All the results described so far have natural analogues for the subvariety \( \mathfrak{h} \oplus \mathfrak{h}^* \) of \( \mathbb{C}^{2n} \). Geometrically, this follows from the observation that the natural additive action of \( \mathbb{C}^2 \) by translation on \( \text{Hilb}^n \mathbb{C}^2 \) gives a decomposition \( \text{Hilb}^n \mathbb{C}^2 = \mathbb{C}^2 \times (\text{Hilb}^n \mathbb{C}^2)/\mathbb{C}^2 \) into a product of varieties [Na, p.10]. Unravelling the actions shows that \( \text{Hilb}^n \mathbb{C}^2/\mathbb{C}^2 \) provides a resolution of singularities for \( \mathfrak{h} \oplus \mathfrak{h}^* \). However, since we need the algebraic consequences of Haiman’s results, we will take a more algebraic approach.

We emphasise that the embedding \( \mathfrak{h} \oplus \mathfrak{h}^* \hookrightarrow \mathbb{C}^{2n} \) is always given by embedding \( \mathfrak{h} \) into the first copy of \( \mathbb{C}^n \) and \( \mathfrak{h}^* \) into the second copy. To fix notation, let \( \mathfrak{h} \) be the hypersurface \( \mathfrak{z} = 0 \) in \( \mathbb{C}^n \) and similarly let \( \mathfrak{h}^* \) be the hypersurface \( \mathfrak{z}^* = 0 \) in the second copy of \( \mathbb{C}^n \); thus \( \mathbb{C}[\mathbb{C}^{2n}] = \mathbb{C}[\mathfrak{h} \oplus \mathfrak{h}^*][\mathfrak{z}, \mathfrak{z}^*] \). Since \( \mathfrak{z}, \mathfrak{z}^* \in \mathbb{C}[\mathbb{C}^{2n}]^W \), this induces the decomposition \( \mathbb{C}[\mathbb{C}^{2n}]^W = \mathbb{C}[\mathfrak{h} \oplus \mathfrak{h}^*]^W[\mathfrak{z}, \mathfrak{z}^*] \). Following the lead of (4.3), we set

\[ A^1 = \mathbb{C}[\mathfrak{h} \oplus \mathfrak{h}^*] \subset A^1 = \mathbb{C}[\mathbb{C}^{2n}] \quad \text{and} \quad J^1 = \mathbb{C}[\mathfrak{h} \oplus \mathfrak{h}^*]A^1 \subset J^1 = \mathbb{C}[\mathbb{C}^{2n}]A^1. \]

We then define \( A^0 = \mathbb{C}[\mathfrak{h} \oplus \mathfrak{h}^*]^W, J^0 = \mathbb{C}[\mathfrak{h} \oplus \mathfrak{h}^*] \) and, for \( d > 1 \), take \( A^d = (A^1)^d \) and \( J^d = (J^1)^d \) for the respective \( d \)-th powers using the multiplication in \( \mathbb{C}[\mathfrak{h} \oplus \mathfrak{h}^*] \). Finally, we write

\[ A = \bigoplus_{i \geq 0} A^i \cong A^0[A^1 t] \quad \text{and} \quad S = \bigoplus_{i \geq 0} J^i \cong \mathbb{C}[\mathfrak{h} \oplus \mathfrak{h}^*][J^1 t] \]

for the corresponding Rees rings. The next result is basic observation about these objects.

**Lemma.** (1) For \( d \geq 0 \), \( A^d = A^d[\mathfrak{z}, \mathfrak{z}^*] \) is the set of polynomials with coefficients from \( A^d \). Similarly, \( J^d = J^d[\mathfrak{z}, \mathfrak{z}^*] \).

(2) Each \( J^d \) is a free module over \( \mathbb{C}[\mathfrak{h}] \) and \( \mathbb{C}[\mathfrak{h}]^W \).
Corollary. The bigraded Poincaré series of $J^d$ is

$$p(J^d, s, t) = \sum_{\mu} P_\mu(s, t)(1-s)(1-t) \Omega(\mu)^{-1} s^{dn(\mu)} t^{dn(\mu')}.$$
4.12. In Corollary 4.13 we will give a singly graded analogue of Corollary 4.11 that will be needed in the proof of the Theorem 1.4. In the proof we will need the following combinatorial formulæ for the fake degrees \( f_\mu(v) \), as defined in (3.9.1).

**Lemma.** Let \( \mu \in \text{Irep}(W) \). Then

1. \( f_\mu(v) = v^N f_\mu'(v^{-1}) \), where \( N = n(n-1)/2 \),
2. \( f_\mu(v) \prod_{x \in d(\mu)} (1 - v^{h(x)}) = v^{n(\mu)} \prod_{i=1}^n (1 - v^i) \), where \( h(x) = 1 + a(x) + l(x) \) as in (2.6),
3. \( \sum_{\lambda} v^{\rho(\lambda)} K_{\lambda\mu}(v^{-1}, v^{-1}) f_\mu(v^{-1}) f_\lambda(1) = \sum_{\lambda} f_\lambda(v^{-1}) f_\mu(1) f_\lambda(1) \).

**Proof.** (1) This is a well-known formula (see, for example, [Op, p.453]).

(2,3) Up to a change of notation, these are both proved within the proof of [Go1, Theorem 6.4]—see the displayed equations immediately after, respectively immediately before [Go1, (18)].

4.13. The \( E \)-grading from (2.4) descends naturally to \( \text{ogr} D(\mathfrak{h}) \cong \mathbb{C}[\mathfrak{h} \oplus \mathfrak{h}^*] \) and we will use the same notation there; thus \( E \)-deg \( \mathfrak{h}^* = 1 \) and \( E \)-deg \( \mathfrak{h} = -1 \). For an \( E \)-graded module (or, indeed, any \( \mathbb{Z} \)-graded module) \( M = \bigoplus_{t \in \mathbb{Z}} M_t \), we write the corresponding Poincaré series as \( p(M, v) = \sum v^i \dim C M_i \). Set

\[
(4.13.1) \quad [n]_v! = \frac{\prod_{i=1}^n (1 - v^i)}{(1 - v)^n}.
\]

**Corollary.** Under the \( E \)-grading, the module \( \mathcal{J}^d = J^d / \mathbb{C}[\mathfrak{h}]^W J^d \) has Poincaré series

\[
(4.13.2) \quad p(\mathcal{J}^d, v) = \frac{\sum_{\mu} f_\mu(1) f_\mu'(v^{-1}) v^{-d(n(\mu) - n(\mu'))} [\mu]_v!}{\prod_{i=2}^n (1 - v^{-i})}.
\]

**Proof.** Since \( \mathbb{C}[\mathfrak{h}]^W \) is \( E \)-graded, so is \( \mathcal{J}^d \), and so the result does make sense. By Lemma 4.4(2), the fundamental invariants of \( \mathbb{C}[\mathfrak{h}]^W \) form an \( r \)-sequence in \( J^d \) for any \( d \geq 0 \). Since these elements have degrees \( 2 \leq r \leq n \), Corollary 4.11 implies that \( \mathcal{J}^d \) has Poincaré series

\[
(4.13.3) \quad p(\mathcal{J}^d, v) = \left( 1 - t \right) \prod_{i=1}^n (1 - s^i) \sum_{\mu} P_\mu(s, t) \Omega(\mu)^{-1} s^{d(\mu)} t^{d(\mu')} s_{v=t=v^{-1}}
\]

where \( P_\mu \) and \( \Omega(\mu) \) are defined in (4.8). Lemma 4.12(2) implies that

\[
(\Omega(\mu))_{s=v, t=v^{-1}} = f_\mu(v)^{-1} f_\mu'(v^{-1})^{-1} \prod_{i=1}^n (1 - v^i)(1 - v^{-i}).
\]

This gives

\[
(4.13.4) \quad p(\mathcal{J}^d, v) = \sum_{\mu} P_\mu(v, v^{-1}) f_\mu(v) f_\mu'(v^{-1}) v^{-d(\mu)} v^{-d(\mu')} \prod_{i=2}^n (1 - v^{-i}).
\]

By Lemma 4.12(3) the numerator of this expression can be described as

\[
(4.13.5) \quad \sum_{\mu} \left( \sum_{\lambda} f_\lambda(v^{-1}) f_\lambda(1) \right) f_\mu(1) f_\mu(v) v^{d(n(\mu) - n(\mu'))}.
\]
Applying Lemma 4.12(1) and using the equality $f_\mu(1) = f_{\mu}(1)$ from (3.9.2) we find that (4.13.5) equals

\begin{equation}
\sum_{\mu} \left( \sum_{\lambda} f_\lambda(v^{-1})f_\lambda(1) \right) f_{\mu'}(1)f_{\mu'}(v^{-1})v^{N}v^{-(n(\mu')-n(\mu))}.
\end{equation}

The standard formula $\sum \text{dim } \mathbb{C}[h]^g_{v^{-i}} = [n]_{v^{-i}}!$ shows that the fake degrees satisfy the identity

$$\sum_{\lambda} f_\lambda(v^{-1})f_\lambda(1) = \prod_{i=1}^{n}(1 - v^{-i}) = [n]_{v^{-1}}!.$$ 

Applying this and (4.13.6) to (4.13.4) we find that

\begin{equation}
p(\overline{J^d}, v) = \frac{\sum_{\mu} f_{\mu'}(1)f_{\mu'}(v^{-1})v^{-(n(\mu')-n(\mu))}v^{N}[n]_{v^{-1}}!}{\prod_{i=2}^{n}(1 - v^{-i})}.
\end{equation}

After changing the order of summation from $\mu$ to $\mu'$ and using the equality

$$v^{N}[n]_{v^{-1}} = v^{N}\prod_{i=1}^{n}(1 - v^{-i}) = \prod_{i=1}^{n}(1 - v^{i}) = [n]_{v}!,$$

(4.13.7) becomes the required equality (4.13.2), and so the corollary is proved. \hfill \Box

5. **Z-algebras**

5.1. Typically in noncommutative algebra—and certainly in our case—one cannot apply the Rees ring construction since one is working with just right modules or homomorphism groups rather than bimodules. One way round this is to use Z-algebras and in this section we describe the basic properties that we need from this theory. The reader is referred to [BP] or [SV, Section 11] for the more general theory and to [BGS, Section 3] for applications of Z-algebras to Koszul duality.

Throughout this paper a Z-algebra will mean a lower triangular Z-algebra. By definition, this is a (non-unital) algebra $B = \bigoplus_{i,j \geq 0} B_{ij}$, where multiplication is defined in matrix fashion: $B_{ij}B_{jk} \subseteq B_{ik}$ for $i \geq j \geq k \geq 0$ but $B_{ij}B_{ik} = 0$ if $j \neq k$. Although $B$ cannot have a unit element, we do require that each subalgebra $B_{ii}$ has a unit element 1, such that $1_{i}b_{ij} = b_{ij} = b_{ij}1_{j}$, for all $b_{ij} \in B_{ij}$.

5.2. Let $B$ be a Z-algebra. We define the category $B\text{-Grmod}$ to be the category of $\mathbb{N}$-graded left $B$-modules $M = \bigoplus_{i \in \mathbb{N}} M_{i}$ such that $B_{ij}M_{j} \subseteq M_{i}$ for all $i \geq j$ and $B_{ij}M_{k} = 0$ if $k \neq j$. Homomorphisms are defined to be graded homomorphisms of degree zero. The subcategory of noetherian graded left $B$-modules will be denoted $B\text{-grmod}$. In all examples considered in this paper $B\text{-grmod}$ will consist precisely of the finitely generated graded left $B$-modules.

A module $M \in B\text{-Grmod}$ is bounded if $M_{n} = 0$ for all but finitely many $n \in \mathbb{Z}$ and torsion if it is a direct limit of bounded modules. We let $B\text{-Tors}$ denote the full subcategory of torsion modules in $B\text{-Grmod}$ and write $B\text{-tors}$ for the analogous subcategory of $B\text{-qgr}$. The corresponding quotient categories are written $B\text{-Qgr} = B\text{-Grmod}/B\text{-Tors}$ and $B\text{-qgr} = B\text{-grmod}/B\text{-tors}$. Write $\pi(M)$ for the image in $B\text{-Qgr}$ of $M \in B\text{-Grmod}$.
5.3. There are two basic examples of $\mathbb{Z}$-algebras that will interest us. For the first, suppose that $S = \bigoplus_{n \geq 0} S_n$ is an $\mathbb{N}$-graded algebra. As in [BGS, Example 3.1.3] we can canonically associate a $\mathbb{Z}$-algebra $\hat{S} = \bigoplus_{i \geq j \geq 0} \hat{S}_{ij}$ to $S$ by setting $\hat{S}_{ij} = S_{i-j}$ with multiplication induced from that in $S$. Define categories $S$-$\text{Qgr}$, $S$-$\text{ogr}$, $S$-$\text{agrr}$ in the usual manner. In particular, $S$-$\text{Grmod}$ denotes the category of $\mathbb{Z}$-graded $S$-modules, from which the other definitions follow as in the last paragraph. We then let $S$-$\text{Grmod}_{\geq 0}$ denote the full subcategory of $S$-$\text{Grmod}$ consisting of $\mathbb{N}$-graded $S$-modules $M = \bigoplus_{i \in \mathbb{N}} M_i$. It is immediate from the definitions that the identity map $\iota : M = \bigoplus_{i \in \mathbb{N}} M_i \to M = \bigoplus_{i \in \mathbb{N}} M_i$ gives equivalences of categories $S$-$\text{Grmod}_{\geq 0} \simeq \hat{S}$-$\text{Grmod}$ and $S$-$\text{ogr}$ implies $\mathbb{Z}$-$\text{ogr}$. For any module $M \in S$-$\text{Grmod}$, one has $\pi(M) = \pi(M_{\geq 0})$ in $S$-$\text{Qgr}$ and so $\iota$ induces category equivalences

\[ S$-$\text{Qgr} \simeq \hat{S}$-$\text{Qgr} \quad \text{and} \quad S$-$\text{ogr} \simeq \hat{S}$-$\text{ogr}. \]  

5.4. For the second class of examples, suppose that we are given noetherian $R$-algebras $R_n$ for $n \in \mathbb{N}$ with $(R_i, R_j)$-bimodules $R_{ij}$, for $i > j \geq 0$. Assume, moreover, that there are morphisms $\theta_{ijk} : R_{ij} \otimes R_j \otimes R_k \to R_{ik}$ satisfying the the obvious associativity conditions. Then we can define a $\mathbb{Z}$-algebra $R_{\mathbb{Z}}$ by $R_{\mathbb{Z}} = \bigoplus_{i \geq j \geq 0} R_{ij}$, where $R_{ii} = R_i$ for all $i$.

A particular example of this construction is the one that interests us. Suppose that $\{R_n : n \in \mathbb{N}\}$ are Morita equivalent algebras, with the equivalence induced from the progenerative $(R_{n+1}, R_n)$-bimodules $P_n$. Define $R_{ij} = P_i \otimes R_i \otimes \cdots \otimes R_{i+2} \otimes P_{i+1} \otimes R_{i+1} \otimes P_j$ and $R_{jj} = R_{ij}$, for $i > j \geq 0$. Tensor products provide the isomorphisms $\theta^{\bullet}_{ij}$ and associativity is automatic. The corresponding $\mathbb{Z}$-algebra $R_{\mathbb{Z}} = \bigoplus_{i \geq j \geq 0} R_{ij}$ will be called the Morita $\mathbb{Z}$-algebra associated to the data $\{R_n, P_n : n \in \mathbb{N}\}$.

5.5. Write $R$-$\text{mod}$ for the category of finitely generated left modules over a noetherian ring $R$. Although easy, the next result provides the foundation for our approach to $U_c$; in order to study $U_c$-$\text{mod}$ it suffices to study $R_{\mathbb{Z}}$-$\text{ogr}$, for any Morita $\mathbb{Z}$-algebra $R_{\mathbb{Z}}$ with $R_0 \cong U_c$.

**Lemma.** Suppose that $R_{\mathbb{Z}}$ is the Morita $\mathbb{Z}$-algebra associated to the data $\{R_n, P_n : n \in \mathbb{N}\}$, where $R_0$ is noetherian.

1. Each finitely generated graded left $R_{\mathbb{Z}}$-module is noetherian.
2. The association $\phi : M \mapsto \bigoplus_{n \in \mathbb{N}} R_{n0} \otimes_{R_0} M$ induces an equivalence of categories between $R_0$-$\text{mod}$ and $R_{\mathbb{Z}}$-$\text{ogr}$.

**Proof.** (1) Any finitely generated graded left $R_{\mathbb{Z}}$-module $M$ is a graded image of $\bigoplus_{a_i} \left( \bigoplus_{j \geq a_i} R_{ja_i} \right) \otimes_{R_0} R_{a_i}$ for some $a_i \in \mathbb{N}$ and so we may assume that $M = \bigoplus_{j \geq a} R_{ja}$, for some $a \geq 0$. Let $L \subseteq M$ be a graded submodule and write $R_{ij}^*$ for the dual of the progenerator $R_{ij}$. Then

\[ X(j) = R_{ja}^* \otimes R_j L_j \subseteq R_{ja}^* \otimes R_j M_j = R_{ja}^* \otimes R_{ja} \xrightarrow{\sim} R_a, \quad \text{for } j \geq a. \]
As $R_a$ is Morita equivalent to $R_0$, it is noetherian and so $\sum_{j \geq a} X(j) = \sum_{i=a}^b X(i)$, for some $b \geq a$. Now,

$$L_k = R_{ka}X(k) \subseteq \sum_{i=a}^b R_{ka}X(i) = \sum_{i=a}^b R_{ki}R_{ia}X(i) = \sum_{i=a}^b R_{ki}L_i \quad \text{for } k \geq a.$$  

Thus $L$ is generated by $L_j$ for $b \geq j \geq a$. Finally, as each $L_i$ is a submodule of the noetherian left $R_0$-module $R_{ia}$, it is finitely generated and hence so is $L$.

(2) Certainly $\phi(M) \in R_2\text{-Grmod}$ and, as $\phi(M)$ is finitely generated by the generators of $R_0M$, one has $\phi(M) \in R_2\text{-grmod}$. Thus $\Phi(M) = \pi\phi(M) \in R_2\text{-agr}$. Since $\Phi$ sends $R_0$-module homomorphisms to graded $R_2$-module homomorphisms, $\Phi$ is a functor.

Conversely, suppose that $\tilde{N} \in R_2\text{-agr}$ and pick a preimage $N \in R_2\text{-grmod}$. Then $N$ is generated by $\bigoplus_{i=0}^\infty N_i$, for some $a$, and so $N_j = R_{ja}N_a$, for all $j \geq a$. For $j \geq i \geq a$ we have natural maps of $R_a$-modules

$$\theta_{ji} : R_{ia}^* \otimes N_i \cong R_{ia}^* \otimes R_{ja} \otimes R_{ji} \otimes N_i \cong R_{ja}^* \otimes (R_{ji} \otimes N_i) \rightarrow R_{ja}^* \otimes N_j,$$

where the tensor products are over the appropriate $R_k$. By the associativity of tensor products, $\theta_{ki} = \theta_{kj}\theta_{ji}$, for all $k \geq j \geq i \geq a$. Since each $N_i$ is a noetherian $R_i$-module, each $R_{ia}^* \otimes N_i$ is a noetherian $R_a$-module and so $\theta_{ji}$ is an isomorphism for all $j \geq i \gg 0$. Equivalently, $N_j \cong R_{ji} \otimes N_i$ for all such $j \geq i$.

Set $\Theta(\tilde{N}) = R_{ja}^* \otimes N_j \in R_0\text{-mod}$ for some $j \gg 0$. Since any two preimages of $\tilde{N}$ in $R_2\text{-grmod}$ agree in high degree, $\Theta(\tilde{N})$ is independent of the choice of $N$. Moreover, as $R_{ja}^* = R_{ja}^* R_{kj}$,

$$\phi(\Theta(\tilde{N}))_{\geq j} \cong \bigoplus_{k \geq j} R_{ka} \otimes R_{ja}^* \otimes N_j \cong \bigoplus_{k \geq j} R_{kj} \otimes N_j = \bigoplus_{k \geq j} N_k,$$

and so $\Phi\Theta(\tilde{N}) = \tilde{N}$. Checking that $\Theta$ and $\Phi$ are inverse equivalences is now routine.

5.6. We remark that many of the standard techniques and results concerned with associated graded modules for unital algebras extend routinely to $\mathbb{Z}$-algebras. These only appear in peripheral ways in this paper and so we refer the reader to [GS] for a discussion of these results.

6. The main theorem

6.1. In this section we prove the main theorem of the paper by proving Theorem 1.4 from the introduction. Indeed we will prove more generally that a version of that theorem holds for all values of $c \in \mathbb{C}$ that satisfy Hypothesis 3.12. As was true with Corollary 3.13 and Proposition 3.16, the theorem will take slightly different forms depending on whether $c \in \mathbb{Q}_{\leq -1}$ or not, so it is convenient to separate the cases with

6.2. Hypothesis. The element $c \in \mathbb{C}$ satisfies Hypothesis 3.12 but $c \notin \mathbb{Q}_{\leq -1}$.

6.3. Assume that Hypothesis 6.2 holds. By Corollary 3.13 there is a Morita equivalence $S_c : U_c\text{-mod} \rightarrow U_{c+1}\text{-mod}$ given by $S_c(M) = Q_{c+1} \otimes U_c M$, where $Q_{c+1} = eH_{c+1}e^{-}\delta \subset D(\mathfrak{h}^{\text{reg}}) * W$ is considered as a right
Corollary. Assume that $U_{c}$ is a $U_{c}$-module via (3.2.1). Following (5.4) we can therefore define a Morita $\mathbb{Z}$-algebra $B(c) = B = U_{\mathbb{Z}}$ associated to the data $\{U_{c+i}, Q_{c+i}^{c+i+1}; i \in \mathbb{N}\}$; thus $B = \bigoplus_{i \geq 0} B_{ij}$ where, for integers $i > j \geq 0$,

\begin{equation}
B_{ij} = U_{c+i} \quad \text{and} \quad B_{ij} = Q_{c+i}^{c+i+1} Q_{c+i-1}^{c+i-2} \cdots Q_{c+j}^{c+j+1},
\end{equation}

where the multiplication in taken in $D(h^{*g}) \ast W$. Note that, by Corollary 3.13, we have a natural isomorphism

\begin{equation}
B_{ij} \cong Q_{c+i-1}^{c+i} \otimes U_{c+i-1} Q_{c+i-2}^{c+i-1} \otimes U_{c+i-2} \cdots \otimes U_{c+j} Q_{c+j}^{c+j+1},
\end{equation}

and so this does accord with the definition in (5.4).

6.4. The Main Theorem. Assume that $c \in \mathbb{C}$ satisfies Hypothesis 6.2. The differential operator filtration $\text{ord}$ on $D(h^{*g}) \ast W$, as defined in (2.3), induces filtrations on the subspaces $B_{ij}$ and hence on $B$, which we will again write as $\text{ord}$. The fact that these filtrations are induced from that of $D(h^{*g}) \ast W$ ensures that the associated graded object

$$\text{ogr} B = \bigoplus_{i \geq 0} \text{ogr} B_{ij}$$

is also a $\mathbb{Z}$-algebra. Similarly, recall from (4.9) the $\mathbb{N}$-graded algebra $A = \bigoplus_{i \geq 0} A_{i}$ associated to Hilb($n$). In this section it is more convenient to use the isomorphic algebra $A = \bigoplus_{i \geq 0} A_{i}^{s}$ to which we canonically associate the $\mathbb{Z}$-algebra $\hat{A} = \bigoplus_{i \geq 0} A_{i}^{s}$, in the notation of (5.3).

Theorem. Assume that $c \in \mathbb{C}$ satisfies Hypothesis 6.2 and define $B$ and $\hat{A}$ as above. Then:

1. There is an equivalence of categories $U_{c}$-$\text{mod} \xrightarrow{\sim} B$-$\text{agr}$.

2. There is an equality $\text{ogr} B = e \hat{A} e$ and hence a graded $\mathbb{Z}$-algebra isomorphism $\text{ogr} B \cong \hat{A}$.

3. $\text{ogr} B$-$\text{agr} \simeq \text{Coh}$ Hilb($n$).

Combining Theorem 6.4 with Corollary 3.13 and the isomorphism $U_{c} \cong U_{c-1}$ from the proof of that result gives:

Corollary. (1) Assume that $c \in \mathbb{C}$ satisfies Hypothesis 3.12. Then there exists a $\mathbb{Z}$-algebra $B'$ such that $U_{c}$-$\text{mod} \simeq B'$-$\text{agr}$ and $\text{ogr} B \cong \hat{A}$. Thus $\text{ogr} B'$-$\text{agr} \simeq \text{Coh}$ Hilb($n$).

2. If $c \in \mathbb{C}$ with $c \not\in \frac{1}{2} + \mathbb{Z}$, then $H_{c}$-$\text{mod} \simeq B'$-$\text{agr}$ and $\text{ogr} B''$-$\text{agr} \simeq \text{Coh}$ Hilb($n$) for some $\mathbb{Z}$-algebra $B''$.

6.5. Analogues of Theorem 6.4 also hold for certain important $U_{c+k}$-modules and we will derive the theorem from one of these. The module in question is the $(U_{c+k}, H_{c})$-bimodule $N(k) = B_{k} e H_{c}$ with the induced $\text{ord}$ filtration coming from the inclusion $N(k) \subset D(h^{*g}) \ast W$. Recall the definition of $J^{*}$ from (4.9).

Proposition. Assume that $c \in \mathbb{C}$ satisfies Hypothesis 6.2 and let $k \in \mathbb{N}$. Then $\text{ogr} N(k) = e J^{k} \delta^{k}$ as submodules of $\text{ogr} D(h^{*g}) \ast W = \mathbb{C}[\mathfrak{h} \oplus \mathfrak{h}^{*}] \ast W$. 

26
\subsection*{6.6. Outline of the proof of the theorem and proposition.} For the rest of the section, we will assume that \( c \in \mathbb{C} \) satisfies Hypothesis 6.2. Thus the notation from (6.3) and (6.4) is available and, by Corollary 3.13, \( N(k) \cong B_{k0} \otimes_U cH_c \) is a progenerative \((U_{c+k}, H_c)\)-bimodule. As will be shown in (6.20), Theorem 6.4 follows easily from Proposition 6.5, so we need only discuss the proof of the latter result. This is nontrivial and will take most of the section but, in outline, is as follows.

It is easy to see that \( eJ^k \delta^k \subseteq \text{ogr} N(k) \) (see Lemma 6.9). The other inclusion is considerably harder. The philosophy behind the proof is to note that we can grade both \( J^k \delta^k \) and \( N(k) \) by the \( E \)-gradation. This is not immediately useful since the graded pieces of the two sides are infinite dimensional but both sides have factor modules for which the graded pieces are finite dimensional. For \( eJ^k \delta^k \cong J^k \delta^k \) the factor is the module \( \overline{F} \delta^k \) described by Corollary 4.13, while the analogous factor \( \overline{N}(k) \) of \( \text{ogr} N(k) \) is described in (6.11) and Corollary 6.14 and is related to the standard modules \( \Delta_{c+k}(\mu) \). The key observation is that these factors have the same Poincaré series and so they are naturally isomorphic as graded vector spaces. The proof of the theorem then amounts to lifting this isomorphism to give the desired equality \( eJ^k \delta^k = \text{ogr} N(k) \).

This also shows that the result has to be non-trivial. Indeed, an alternative proof of the proposition (or the theorem) would also provide an alternative proof to a number of the results from [Ha3].

\subsection*{6.7.} We start with two elementary observations that will be used frequently. If \( R = \bigcup F^i R \) is a filtered ring and \( r \in F^m R \smallsetminus F^{m-1} R \), we write \( \sigma(r) = [r + F^{m-1} R] \in \text{gr}_F^m R \) for the \textit{principal symbol} of \( r \).

\textbf{Lemma.} \textit{Let} \( R = \bigcup F^i R \) \textit{be a filtered} \( k \)-\textit{algebra, for a field} \( k \).

\textit{(1)} \textit{Let} \( A, B \) \textit{be subspaces of} \( R \) \textit{and give} \( A, B \) \textit{and} \( AB \) \textit{the induced filtration} \( F \). \textit{Then} \( (\text{gr}_F A)(\text{gr}_F B) \subseteq \text{gr}_F AB \) \textit{as subspaces of} \( \text{gr}_F R \). \textit{Indeed, if} \( a \in A \) \textit{and} \( b \in B \) \textit{satisfy} \( \sigma(a)\sigma(b) \neq 0 \), \textit{then} \( \sigma(a)\sigma(ab) = \sigma(ab) \).

\textit{(2)} \textit{Suppose that} \( A = \bigcup F^i A \) \textit{is a filtered right} \( R \)-\textit{module and that} \( B = \bigcup F^i B \) \textit{is a filtered left} \( R \)-\textit{module and give the vector space} \( A \otimes_R B \) \textit{the tensor product filtration:} \( F^n(A \otimes B) = \sum F^i A \otimes F^{n-i} B \). \textit{Then there is a natural surjection} \( \text{gr}_F A \otimes_{\text{gr}_R} \text{gr}_F B \rightarrow \text{gr}_F (A \otimes_R B) \).

\textit{Proof.} \textit{(1)} \textit{Identify} \( \text{gr}_F A = \bigoplus (F^n A + F^{n-1} R)/F^{n-1} R \subseteq \text{gr}_F R \) \textit{so that the result makes sense}. \textit{Suppose that} \( \tilde{a} \in \text{gr}_F^m A \) \textit{and} \( \tilde{b} \in \text{gr}_F^m B \) \textit{are such that} \( \tilde{a}\tilde{b} \neq 0 \) \textit{in} \( \text{gr}_F R \). \textit{Lift} \( \tilde{a} \) \textit{to} \( a \in F^n A \) \textit{and} \( \tilde{b} \) \textit{to} \( b \in F^m B \). \textit{Then, as elements of} \( \text{gr}_F R \), \textit{one has} \( \tilde{a}\tilde{b} = [a + F^{n-1} R] [b + F^{m-1} R] \subseteq [ab + F^{n+m-1} R] \). \textit{Since} \( \tilde{a}\tilde{b} \neq 0 \), \textit{ab} \textit{in} \( F^{n+m} \smallsetminus F^{n+m-1} R \), \textit{whence} \( \tilde{a}\tilde{b} = \sigma(ab) \) \textit{is the image of} \( ab \) \textit{in} \( \text{gr}_F (AB) \).

\textit{(2)} \textit{Define a map} \( \rho : \text{gr}_F A \times \text{gr}_F B \rightarrow \text{gr}_F (A \otimes_R B) \) \textit{by} \( \rho(\tilde{a}, \tilde{b}) = [a \otimes b + F^{n+m-1} (A \otimes B)] \), \textit{for} \( \tilde{a} \in \text{gr}_F^m A \), \( \tilde{b} \in \text{gr}_F^m B \) \textit{and where the rest of the notation is the same as for part (1)}. \textit{This clearly defines a} \( C \)-\textit{bilinear map that is} \( \text{gr}_F R \)-\textit{balanced in the sense that} \( \rho(\tilde{a} \tilde{r}, \tilde{b}) = \rho(\tilde{a}, \tilde{r} \tilde{b}) \) \textit{for} \( \tilde{r} \) \textit{in} \( \text{gr}_F R \). \textit{By universality,} \( \rho \) \textit{therefore induces a map} \( \text{gr}_F A \otimes_{\text{gr}_R} \text{gr}_F B \rightarrow \text{gr}_F (A \otimes_R B) \). \textit{It is surjective since} \( F^{n+m} (A \otimes B)/F^{n+m-1} (A \otimes B) \) \textit{is spanned by elements of the given form} \( [a \otimes b + F^{n+m-1} (A \otimes B)] \). \( \square \)

\subsection*{6.8. Lemma.} \textit{Let} \( R = \bigcup_{i \geq 0} F^i R \) \textit{be a filtered ring, pick} \( r \in R \) \textit{and let} \( I \) \textit{be a subset of} \( R \). \textit{Under the induced filtrations,} \( \text{gr}_F (rI) = \sigma(r) \text{gr}_F (I) \) \textit{in the following cases:}
Proof. Assume that \( r \in F^sR \setminus F^{s-1}R \). We claim that, in both cases, it suffices to prove that \( F^n(rI) = rF^{n-s}I \) for all \( n \geq s \). Indeed, if this is true then the identity \( F^n(rI) = rI \cap F^nR \) implies that the \( n \)th summand of \( \text{gr}(rI) \) equals

\[
\frac{F^n(rI)}{F^{n-1}(rI)} = \frac{F^n(rI) \cap F^{n-1}R}{F^{n-1}R} = \frac{rF^{n-s}I + F^{n-1}R}{F^{n-1}R},
\]

which is the \( n \)th summand of \( \sigma(r)\text{gr}(I) \).

1. In this case, \( rt \in F^n(rI) = rI \cap F^n(R) \Leftrightarrow t \in I \) and \( t \in F^{n-s}R \), as required.

2. Here, \( rF^nI \subseteq F^n(rI) \) whence \( rF^nI = r^2F^nI \subseteq rF^n(rI) \subseteq rF^nI \). Since \( rF^n(rI) = F^n(rI) \) this implies that \( rF^n(I) = F^n(rI) \). \( \square \)

Example. It is easy to check that some hypotheses are required for the lemma to hold. For example, filter the polynomial ring \( R = \mathbb{C}[x,y] \) by \( x, xy \in F^0R \) but \( y \in F^1R \). Then \( x, xy \in F^0(xR), \) yet \( xy \notin \sigma(x)\text{gr}_F R \).

6.9. We now turn to the proof of Proposition 6.5. As was mentioned in (6.6) the inclusion \( J^k \delta^k e \subseteq \text{ogr} N(k) \) is easy.

Lemma. (1) For \( i \geq j \geq 0 \) we have \( e(A^{i-j} \delta^{i-j})e \subseteq \text{ogr} B_{ij} \).

(2) The inclusion of part (1) is an equality for \( i = j \) and for \( i = j + 1 \).

(3) For \( k \geq 0 \) there is an inclusion \( eJ^k \delta^k \subseteq \text{ogr} N(k) \) of left \( eA^0 \)e-modules. This is an equality for \( k = 0 \).

Proof. (2) By the PBW Theorem 2.2.1, \( \text{ogr} B_{ii} = e(\mathbb{C}[h \oplus h^*] \ast W)e \) and so the claim holds for \( i = j \). Similarly, since \( e, \delta \in \text{ord}_0(D(h^{reg}) \ast W) \) and \( \delta \) is regular in \( \text{ogr}(D(h^{reg}) \ast W) \), Lemma 6.8 implies that

\[
\text{ogr} B_{j+1,j} = \text{ogr}(eH_{c,j+1}e \delta) = e(\text{ogr} H_{c,j+1}e \delta) = e(\mathbb{C}[h \oplus h^*] \ast W)e \delta = eA^1 \delta e.
\]

(1) Combining part (2) with Lemma 6.7(1) and induction shows that

\[
(eA^1 \delta^1 e)^{i-j} \subseteq \text{ogr} B_{i,i-1} \cdots \text{ogr} B_{j+1,j} = \text{ogr} B_{ij}.
\]

(3) When \( k = 0 \), the assertion \( eJ^k \delta^k = \text{ogr} N(k) \) is just the statement that \( e\mathbb{C}[h \oplus h^*] = e(\mathbb{C}[h \oplus h^*] \ast W) \).

When \( k > 0 \), part (i) and Lemma 6.7 give \( eJ^k \delta^k = eA^k \delta^k e\mathbb{C}[h \oplus h^*] \ast W \subseteq \text{ogr} B_{k0} \text{ogr}(eH_0) \subseteq \text{ogr} N(k) \). \( \square \)

6.10. The next several results will be aimed at getting a more detailed understanding of the bimodule structure of \( N(k) \) and its factors. For the most part we are interested in their graded structure for which the actions of the elements \( h_{c+t} \in H_{c+t} \) from (2.4.1) are particularly useful. Given an \( (U_{c+s}, U_{c+t}) \)-bimodule \( M \), define

\[
h \cdot m = h_{c+s}m - m h_{c+t} \text{ for any } m \in M.
\]

When \( s = t \) this is just the adjoint action of \( h_{c+s} \) on \( M \).
Lemma. (1) $\text{ch}_{c+t-1}e = \delta^{-1}e\_h e\_\delta$.

(2) The action of $h$ is diagonalisable on the modules $N(i)$, $B_{ij}$ and $M(i) = H_{c+t}eB_{0i}$, for any $i \geq j \geq 0$.

Proof. (1) Use the first paragraph of the proof of [Go2, Theorem 4.10].

(2) We start with the $B_{ij}$. If $b_1 \in B_d$ and $b_2 \in B_{ij}$, then $h \cdot (b_1b_2) = (h \cdot b_1)b_2 + b_1(h \cdot b_2)$. Thus, by induction, it suffices to prove the result for each $B_{i,t-1} = eH_{c+t}\delta e$. Clearly $e\text{ch} = h\text{e}$. Thus, by part (1), for any $m \in H_{c+t}$ we have

\[
(6.10.1) \quad h \cdot em\delta e = h_{c+t}em\delta e - em\delta eh_{c+t-1} = eh_{c+t}m\delta e - em\delta(\delta^{-1}e\_h e\_\delta) = e(h_{c+t}, m)\delta e.
\]

By (2.4.2) $H_{c+t}$ is diagonalisable under the adjoint $h_{c+t}$-action and so the result for $B_{ij}$ follows. The same argument works for the modules $N(i)$ and $M(i)$ if one uses the decompositions $N(i) = (B_{0i})(eH_c)$ and $M(i) = (H_{c+t})(B_{0i})$.

6.11. The factors of $N(k)$ that most interest us are defined as follows. Since $N(k)$ is a $(U_{c+k}, H_c)$-bimodule, the embeddings $\mathbb{C}[h]^W \to U_{c+k}$ and $\mathbb{C}[h^*] \to H_c$ make $N(k)$ into a $(\mathbb{C}[h]^W, \mathbb{C}[h^*])$-bimodule. Let $C$ be the trivial module over either $\mathbb{C}[h]^W$ or $\mathbb{C}[h^*]$ and set $\overline{N(k)} = C \otimes_{\mathbb{C}[h]^W} N(k)$ and $\overline{N(k)} = N(k) \otimes_{\mathbb{C}[h^*]} C$. As $\mathbb{C}$ is a graded $h$-module, the adjoint action of $h$ on $\overline{N(k)}$ from Lemma 6.10 induces a $\mathbb{Z}$-grading, again called the $h$-grading, on both $\overline{N(k)}$ and $\overline{N(k)}$. If an element $b$ from any of these three modules has degree $n$ in this grading we write $h\text{-deg}(b) = n$. The reader should note that, as will be explained in (6.14), this is not the same as the $E$-gradation on these modules.

The next result gives the elementary properties of these modules.

Lemma. (1) For any $i \geq j \geq 0$, $B_{ij} \subseteq U_{c+i} \cap U_{c+j}$.

(2) For $k \geq 0$, both $N(k)$ and $U_{c+k}$ are free left $\mathbb{C}[h]^W$-modules, while $N(k)$ is a free right $\mathbb{C}[h^*]$-module.

(3) $N(k)$ is a finitely generated, free left $\mathbb{C}[h]^W$-module.

(4) Similarly, $\overline{N(k)}$ is a finitely generated, free right $\mathbb{C}[h^*]$-module.

Proof. We will use frequently and without comment the fact that $\mathbb{C}[h^*]$ is a free $\mathbb{C}[h^*]^W$-module. Moreover, as $\mathbb{C}[h^*]^W$ is a polynomial ring, any projective $\mathbb{C}[h^*]^W$ is free by the Quillen-Suslin Theorem.

(1) By induction, we may assume that $i = j + 1$. The inclusion $B_{ij} = eH_{c+t}e \subseteq U_{c+i}$ is immediate. If $p \in H_{c+t}$, then, by (3.2.1),

\[
epc_\delta = e\delta^{-1}\delta pc_\delta = \delta^{-1}e\_\delta pc_\delta \in \delta^{-1}e\_H_{c+t}e_\delta = U_{c+j}.
\]

(2) By the PBW Theorem 2.2.1, each $H_d$ is free as a left $\mathbb{C}[h]$-module and as a right $\mathbb{C}[h^*]$-module. Therefore, $H_d$ is a free left $\mathbb{C}[h]^W$-module as is its summand $Hde$. Under the left action of $W$, $(Hde)^W = eHde$ since, if $fe \in (Hde)^W$, then $fe = [W]^{-1}\sum_{w \in W} wefe = efe$. But $(Hde)^W$ is a $W$-module summand of $Hde$, while the actions of $W$ and $\mathbb{C}[h]^W$ commute. Thus $U_d = (Hde)^W$ is a $\mathbb{C}[h]^W$-module summand of $Hde$ and
hence is free. By Corollary 3.13, \( N(k) \cong B_{k0} \otimes_{U_c} eH_c \) is a projective left \( U_{c+k} \)-module and hence a free left \( \mathbb{C}[h]^W \)-module.

On the other hand, \( N(k) \) is a projective right \( H_c \)-module and hence a projective right \( \mathbb{C}[h^*] \)-module.

(3) Set \( X = H_c \otimes_{\mathbb{C}[h^*]} C \). Clearly \( X \in \mathcal{O}_c \) in the sense of (2.7) and, by (2.2.1), \( X \cong \mathbb{C}[h] \otimes_{\mathbb{C}} W \) as left \( \mathbb{C}[h] \ast W \)-modules. Thus \( X \) is a finitely generated free left \( \mathbb{C}[h] \)-module and so, by [GGOR, Proposition 2.21], \( X \) has a filtration whose factors are standard modules.

By definition, \( \overline{N(k)} = eM \) where \( M = \tilde{S}_{c+k-1} \circ \cdots \circ \tilde{S}_c(X) \), in the notation of (3.2). By Proposition 3.16 \( M \) also has a finite filtration by standard modules and so [GGOR, Proposition 2.21] shows that \( M \) is a finitely generated free module over \( \mathbb{C}[h] \) and hence over \( \mathbb{C}[h]^W \). Thus, so is its summand \( eM \).

(4) We first show that \( N(k) \) is a finitely generated right module over \( R = (\mathbb{C}[h]^W)^{\text{op}} \otimes_{\mathbb{C}} \mathbb{C}[h^*] \). By part (1), \( B_{k0} \subseteq U_c \) and so \( N(k) \subseteq eH_c \). Thus \( \text{ogr} N(k) \subseteq \text{ogr} H_c = \mathbb{C}[h \oplus h^*] \ast W \), which is certainly a noetherian \( \mathbb{C}[h]^W \otimes \mathbb{C}[h^*] \)-module. Since the \( \text{ord} \) filtration on \( N(k) \) is the one induced from \( D(h^{\text{reg}}) \ast W \), the actions of \( \mathbb{C}[h]^W \) and \( \mathbb{C}[h^*] \) on \( \text{ogr} N(k) \) are the natural ones induced from the actions of those rings on \( N(k) \subset D(h^{\text{reg}}) \ast W \). In other words, the given \( R \)-module structure of \( \text{ogr} N(k) \) is the one induced from the \( R \)-module structure of \( N(k) \). Since the former module is finitely generated, so is the latter.

Let \( y_1, \ldots, y_{n-1} \) be the generators of \( \mathbb{C}[h^*] \) and let \( q_1, \ldots, q_{n-1} \) be the fundamental invariants of \( \mathbb{C}[h]^W \). By (2), the \( \{y_j\} \) form an \( r \)-sequence in \( N(k) \), while (3) implies that the \( \{q_j\} \) form an \( r \)-sequence in the factor \( \overline{N(k)} = N(k)/\sum N(k)y_j \) as a module over \( \mathbb{C}[h]^W = R/\sum y_j R \). Thus \( \Sigma = \{y_\ell q_m : 1 \leq \ell, m \leq n - 1 \} \) is a regular sequence for the right \( R \)-module \( N(k) \). In particular, if \( n = \sum y_\ell R + q_\ell R \), then \( \Sigma \) is an \( r \)-sequence for the \( R_n \)-module \( N(k)_n \). By the Auslander-Buchsbaum formula [Mt, Ex. 4, p.114], \( N(k)_n \) is therefore free as a \( R_n \)-module.

Finally, consider \( \overline{\overline{N(k)}} = N(k)/\sum q_j N(k) \). Under the induced \( h \)-grading, \( \overline{\overline{N(k)}} \) is a finitely generated, graded \( \mathbb{C}[h^*] \)-module and so corresponds to a \( \mathbb{C}^* \)-equivariant coherent sheaf on \( h^* \). As a result the locus where \( \overline{\overline{N(k)}} \) is not free is a \( \mathbb{C}^* \)-stable closed subvariety of \( h^* \). If this locus is non-empty it must contain the unique \( \mathbb{C}^* \)-fixed point \( p = (y_1, \ldots, y_{n-1}) \) for this expanding \( \mathbb{C}^* \)-action. But then \( (N(k))_p \) would not be free, contradicting the conclusion of the last paragraph.

\[ \square \]

6.12. We next need to understand the graded structure of the modules \( \overline{N(k)} \) and \( N(k) \) under the \( h \)-grading. To do this, we express \( N(0) \) as a weighted sum of standard modules in the Grothendieck group \( G_0(U_c) \) and then to use Proposition 3.16 to write \( \overline{N(k)} = B_{k0} \otimes N(0) \) in a similar manner. This is quite delicate since there are some subtle shifts involved and we first want to understand these shifts for \( B_{ij} \otimes \Delta_c(\mu) \).

We will need to work with the following graded version \( \tilde{O}_d \) of \( O_d \) constructed in [GGOR, Section 2.4]. The objects \( M \) in \( \tilde{O}_d \) are finitely generated \( H_d \)-modules on which \( \mathbb{C}[h^*] \) acts locally nilpotently and which come equipped with a \( \mathbb{Z} \)-grading \( M = \bigoplus_{r \in \mathbb{Z}} M_r \) such that \( pM_r \subseteq M_{r+\ell} \) for each \( p \in H_d \) with \( \mathbf{E} \text{-deg}(p) = \ell \). The morphisms are homogeneous \( H_d \)-module homomorphisms of degree zero. A \textit{graded standard module} \( \tilde{\Delta}_d(\mu) \), isomorphic to \( \Delta_d(\mu) \) as an ungraded module, is given by setting \( \tilde{\Delta}_d(\mu)_r = \mathbb{C}[h]_r \otimes \mu \). By local nilpotence and
finite generation, each weight space of a module \( M \in \mathcal{O}_d \) is finite dimensional and so \( M \) has a well-defined Poincaré series. There is a degree shift functor \([1]\) in \( \mathcal{O}_d \) defined by \( M[1]_r = M_{r-1} \). By abuse of notation, \( \mathcal{O}_d \) will also denote the corresponding category of graded \( U_d \)-modules.

**Lemma.** Fix \( i \geq j \geq 0 \) and \( \mu \in \text{Irrep}(W) \). Give \( B_{ij} \) the adjoint \( h \)-grading and let \( B_{ij} \otimes U_{c+j} e \tilde{\Delta}_{c+j}(\mu) \) have the grading this induces. Then \( B_{ij} \otimes U_{c+j} e \tilde{\Delta}_{c+j}(\mu) \in \mathcal{O}_{c+i} \) and, as elements of that category,

\[
B_{ij} \otimes U_{c+j} e \tilde{\Delta}_{c+j}(\mu) \cong e \tilde{\Delta}_{c+i}[(i-j)(n(\mu) - n(\mu'))].
\]

**Proof.** Write \( \nabla = B_{ij} \otimes U_{c+j} e \tilde{\Delta}_{c+j}(\mu) \) and let \( \deg_{e_{c+j}} \) denote the degree function in \( \mathcal{O}_{c+i} \). By hypothesis, the graded structure of an element \( b \otimes v \in \nabla \) is given by \( \deg(b \otimes v) = h \)-deg \( (b \otimes v) = h \)-deg \( b + \deg_{e_{c+j}}(v) \). Proposition 3.16 implies that (as ungraded modules)

\[
(6.12.1) \quad \nabla = S_{c+i} \circ \cdots \circ S_{c+j+1}(e \Delta_{c+j}(\mu)) \cong e \Delta_{c+i}(\mu).
\]

Thus, under its given grading, \( \nabla \in \mathcal{O}_{c+i} \).

Unfortunately, it is not easy to write the generator \( e \otimes \mu \) of \( e \Delta_{c+i}(\mu) \) as an element of \( \nabla \) and for this reason the shift in the grading in (6.12.1) is subtle. In order to understand this we will use the canonical grading from (3.8) and we write the corresponding degree function as \( \deg_{\text{can}} \). The advantage of this grading is that it is simply given by the left multiplication of \( h_{c+i} \). Thus, as (6.12.1) is an isomorphism of left \( U_{c+i} \)-modules and hence of left \( \mathbb{C}[h_{c+i}] \)-modules, it is automatically a graded isomorphism under the canonical grading.

Since \( h^* \) has \( E \)-degree 1, the canonical grading on \( \Delta_d(\mu) \), for any \( d \in \mathbb{C} \), is a shift of the grading on \( \tilde{\Delta}_d(\mu) \). The shift is easy to compute. By definition, the generator \( 1 \otimes \mu \) of \( \tilde{\Delta}_d(\mu) \) has \( \deg_d(1 \otimes \mu) = 0 \) whereas, by Proposition 3.10, the generator \( 1 \otimes \mu \) of \( \Delta_d(\mu) \) has

\[
\deg_{\text{can}}(1 \otimes \mu) = D(d, \mu) = (n-1)/2 + d(n(\mu) - n(\mu')).
\]

We may therefore regard \( \Delta_d(\mu) \) as being in \( \mathcal{O}_d \), in which case

\[
(6.12.2) \quad \Delta_d(\mu) = \tilde{\Delta}_d(\mu)[D(d, \mu)].
\]

Let \( b \in B_{ij} \) with \( h \)-deg \( (b) = r \) and suppose that \( v \in e \Delta_{c+j}(\mu) \) has deg \( \text{can} \)(\( v \)) = \( s \). Then

\[
h_{c+i} \cdot b \otimes v = (h \cdot b) \otimes v + b h_{c+j} \otimes v = (h \cdot b) \otimes v + b \otimes h_{c+j} v = (r + s)b \otimes v.
\]

Thus \( \deg_{\text{can}} (b \otimes v) = h \)-deg \( (b) + \deg_{\text{can}} (v) \). Finally, (6.12.2) implies that

\[
\deg_{c+i}(b \otimes v) = \deg_{\text{can}} (b \otimes v) - D(c + i, \mu) = h \)-deg \( (b) + \deg_{\text{can}} (v) - D(c + i, \mu)
\]

\[
= h \)-deg \( (b) + \deg_{\text{can}} (v) + D(c + j, \mu) - D(c + i, \mu)
\]

\[
= \deg (b \otimes v) + (j - i)(n(\mu) - n(\mu')),
\]

as required. \( \square \)
6.13. Given a \( \mathbb{Z} \)-graded complex vector space \( M = \bigoplus_{r \in \mathbb{Z}} M_r \) such that \( \dim_C M_r \) is finite for all \( r \) then, as in (4.13), we define the Poincaré series of \( M \) to be \( p(M, v) = \sum v^r \dim_C M_r \). Each \( N(k) \) is graded via the adjoint \( h \) action from (6.11), although of course the summands are infinite dimensional. Thus in order to understand the more detailed structure of \( N(k) \) and \( \text{ogr} N(k) \) we will consider the Poincaré series of the factor modules \( \overline{N(k)} \) and \( N(k) \).

**Proposition.** If \( \overline{N(k)} \) as graded via the adjoint \( h \) action on \( N(k) \), then its Poincaré series is

\[
(6.13.1) \quad p(\overline{N(k)}, v) = \frac{\sum_{\mu} f_\mu(1) f_\mu(v^{-1}) v^{-k(n(\mu) - n(\mu'))}[\mu]!}{\prod_{i=2}^n (1 - v^{-i})}.
\]

**Proof.** We first calculate the Poincaré series for \( N(k) \), and we begin with \( N(0) \). As in the proof of Lemma 6.11(3), \( X = H_c \otimes_{\mathbb{C}[h^*]} \mathbb{C} \) is an object of \( \overline{\mathcal{O}_c} \), where the grading is the natural one defined by \( \deg(1 \otimes 1) = 0 \). By construction, \( eX \cong N(0) \) and this is a graded isomorphism since the adjoint \( h \)-graded structure of \( N(0) = U_c/I \) is simply defined by \( h \)-grading. By (2.2.1) we have a graded isomorphism \( X \cong \mathbb{C}[h] \otimes \mathbb{C} W \). Applying \( (\mathbb{C} \otimes_{\mathbb{C}[h]} -) \) to the formula \( [X] = \sum_{\mu} p_\mu[\Delta_c(\mu)] \) therefore yields \( \mathbb{C} W = \sum_{\mu} p_\mu[\mu] \).

Finally, we calculate the Poincaré series of \( \overline{N(k)} \). By Lemma 6.11(2,3), an \( h \)-homogeneous basis for this module is given by lifting a homogeneous \( C \)-basis from \( \overline{N(k)} \otimes_{\mathbb{C}[h^*]} \mathbb{C} = \mathbb{C} \otimes_{\mathbb{C}[h]} \overline{N(k)} \). Thus, combining (6.13.3) with the formulae \( p(\mathbb{C}[h]^W, v) = \prod_{i=2}^n (1 - v^{-i}) \) and \( p(\mathbb{C}[h^*], v) = (1 - v^{-1})^{-n} \) gives

\[
(6.13.4) \quad p(\overline{N(k)}, v) = \frac{\sum_{\mu} f_\mu(1) f_\mu(v) e^{k(n(\mu) - n(\mu'))}}{(1 - v^{-1})^{n-1}}.
\]

This needs to be adjusted to yield (6.13.1). Set \( N = n(n - 1)/2 \). Then Lemma 4.12(1) and (3.9.2) combine to show that

\[
\sum_{\mu} f_\mu(1) f_\mu(v) e^{k(n(\mu) - n(\mu'))} = \sum_{\mu} f_{\mu'}(1) f_{\mu'}(v^{-1}) e^{k(n(\mu) - n(\mu'))} = v^N \sum_{\lambda} f_\lambda(1) f_\lambda(v^{-1}) e^{k(n(\lambda) - n(\lambda))}.
\]
Moreover, rearranging (4.13.1) gives
\[ [n]_v = \prod_{i=1}^{n} \frac{1 - v^i}{1 - v} = v^n \frac{\prod_{i=1}^{n} (1 - v^{-i})}{(1 - v^{-1})^n}. \]

Combining these formul\ae{} with (6.13.4) gives (6.13.1).

6.14. Recall the Euler gradation \( E \)-deg on \( D(\mathfrak{h}^{\text{reg}}) \ast W \) and its subrings from (2.4). Since \( e, e_- \) and \( \delta \) are homogeneous under this action, each \( Q_{c+\ell+1}^{c+\ell} \) and hence each \( B_{ij} \) and \( N(k) \) is also graded under this action. As in (2.4), this induces a graded structure, again called \( E \)-deg, on \( \text{ogr} B_{ij} \) and \( \text{ogr} N(k) \). Since the fundamental invariants of \( \mathbb{C}[\mathfrak{h}]^W \) are \( E \)-homogeneous, the \( E \)-grading on \( N(k) \) descends to gradings on \( N(k) \) and \( N(k) \). Similarly, each \( A^u \delta^u \) and \( J^u \delta^u \) has an \( E \)-grading induced from that on \( \mathbb{C}[\mathfrak{h} \oplus \mathfrak{h}^*] \) and hence so does \( A = \bigoplus_{n \geq 0} A^n \delta^n \).

However, the \( E \)-grading on \( B_{k0} \) and hence on \( N(k) \) is not equal to the adjoint \( h \)-grading. The problem is that, in (6.10.1), the adjoint \( h \) action does not “see” the element \( \delta \). Thus if we wish to relate the Poincaré series of \( N(k) \) to that of \( J^k \delta^k \) we need the following slight modification of Proposition 6.13.

**Corollary.** Let \( k \geq 0 \), set \( N = n(n-1)/2 \) and write \( K = kN \).

1. If \( b \in B_{ij} \) for \( i \geq j \geq 0 \) is homogeneous under the \( h \)-grading then it is homogeneous in the \( E \)-grading and \( E \)-deg \( b = (i-j)N + h \)-deg \( b \).

2. Under the \( E \)-grading, \( N(k) \) has Poincaré series
\[ p(N(k), v) = v^K \frac{\sum_{\mu} f_\mu(1)f_\mu(v^{n-1})v^{-k(n(\mu)-n(\mu'))}([n]_v)!}{\prod_{i=2}^{n}(1-v^{-i})}. \]

while \( N(k) \) has Poincare series
\[ p(N(k), v) = v^K \frac{\sum_{\mu} f_\mu(1)f_\mu(v)\delta^{k(n(\mu)-n(\mu'))}}{\prod_{i=2}^{n}(1-v^{-i})}. \]

**Proof.** (1) If \( b_1 \in B_{ik} \) and \( b_2 \in B_{kj} \) then \( h \cdot (b_1 b_2) = (h \cdot b_1) b_2 + b_1 (h \cdot b_2) \) and \( [E, b_1 b_2] = [E, b_1] b_2 + b_1 [E, b_2] \). By induction, it therefore suffices to prove the result when \( b = em\delta e \in B_{k,k-1} = eH_{c+k}\delta e \), for some \( k > 0 \). By (6.10.1) we see that \( h \cdot b = e[h_{c+k}, m]\delta e \) whereas \( [E, b] = e[E, m]\delta e + em[E, \delta]e \). By (2.4), \( [h_{c+k}, m] = [E, m] \) and so the two gradings differ by \( E \)-deg \( \delta = N \).

(2) This follows from part (1) combined with Proposition 6.13, respectively (6.13.3).

6.15. Fix \( k \geq 0 \) and for notational simplicity write \( J = eJ^k \delta^k \) and \( N = N(k) \). The final step in the proof of Proposition 6.5 is to show that the inclusion \( \Theta : J \hookrightarrow \text{ogr} N \) from Lemma 6.9(3) is surjective. In order to effectively use Corollary 6.14, we do this by lifting \( \Theta \) to \( \mathbb{C}[\mathfrak{h}]^W \)-module map \( \theta : J \rightarrow W \). The order filtration on \( D(\mathfrak{h}^{\text{reg}}) \ast W \) induces a graded structure on \( \text{ogr} D(\mathfrak{h}^{\text{reg}}) \ast W \cong \mathbb{C}[\mathfrak{h}^{\text{reg}} \oplus \mathfrak{h}^*] \ast W \) and hence on \( \text{ogr} N \), which we call the order gradation; thus \( \text{deg}_{\text{ord}}(\mathbb{C}[\mathfrak{h}] \ast W) = 0 \), while \( \text{deg}_{\text{ord}} \mathfrak{h} = 1 \). We will use the same terminology for the induced grading on the rings \( A^0 = \mathbb{C}[\mathfrak{h} \oplus \mathfrak{h}^*]^W \) and \( A \) and the module \( J \).
Let \( N^m = \text{ord}^m N \) denote the elements in \( N \) of order \( \leq m \). Similarly, write \( \mathcal{J} = \bigoplus_{m \geq 0} \text{ogr}^m \mathcal{J} \) for the graded structure of \( \mathcal{J} \) under the \( \text{ord} \) gradation and write the induced order filtration as \( \mathcal{J} = \bigcup \mathcal{J}^m \), for \( \mathcal{J}^m = \text{ord}^m \mathcal{J} = \bigoplus_{0 \leq i \leq m} \text{ogr}^i \mathcal{J} \).

**Lemma.** There exists an injective map \( \theta : \mathcal{J} \rightarrow N \) of left \( C[h]W \)-modules such that:

1. \( \theta \) is a graded homomorphism under the \( E \)-gradation and is a filtered homomorphism under the order filtration.

2. The associated graded map \( \text{ogr} \theta : \mathcal{J} \rightarrow \text{ogr}N \) induced by \( \theta \) is precisely \( \text{ogr} \theta = \Theta \).

**Proof.** Trivially, \( \Theta \) is an \( E \)-graded map (by which we always mean a graded map of degree zero), as well as being graded under the \( \text{ord} \) gradation. For any \( m \), \( \text{ogr}^m \mathcal{J} \) is an \( E \)-graded \( C[h]W \)-module. By Corollary 4.9(2) \( \mathcal{J} \) is a free left \( C[h]W \)-module, and hence so is each summand \( \text{ogr}^m \mathcal{J} \). Thus we may pick an \( E \)-homogeneous free basis \( \{ a_{jm} \} \) for \( \text{ogr}^m \mathcal{J} \). Now \( a_{jm} = \Theta(a_{jm}) \in \text{ogr}^m N = N^m/N^{m-1} \) and the surjection \( \pi_m : N^m \rightarrow N^m/N^{m-1} \) is an \( E \)-graded surjection. Thus, for each \( j, m \) we can pick an \( E \)-homogeneous preimage \( \theta(a_{jm}) \in N^m \) of \( \Theta(a_{jm}) \).

Define \( \theta \) to be the \( C[h]W \)-module map induced by the map \( a_{jm} \mapsto \theta(a_{jm}) \) on basis elements. Since \( \pi_m \) is a left \( C[h]W \)-module map, a straightforward induction on orders of elements ensures that the \( \theta(a_{jm}) \in N^m \) are a free basis for the module they generate. The other conclusions of the lemma follow automatically from the construction of \( \theta \).

6.16. As happens with many questions about \( W \)-invariants, it is easy to prove that \( \Theta \) is surjective on \( h^{\text{reg}} \). Given a left \( C[h]W \)-module \( M \), we will write \( M[\delta^{-2}] \) for the localisation \( C[h]W[\delta^{-2}] \otimes_{C[h]W} M \). Clearly, when \( M \) is a left \( C[h] \)-module, \( M[\delta^{-2}] \) is naturally isomorphic to \( C[h][\delta^{-1}] \otimes_{C[h]} M \).

**Lemma.** (1) The inclusion \( \Theta[\delta^{-2}] : \mathcal{J}[\theta^{-2}] \hookrightarrow (\text{ogr}N)[\delta^{-2}] \) is an equality.

(2) The induced map \( \theta[\delta^{-2}] : \mathcal{J}[\theta^{-2}] \rightarrow N[\delta^{-2}] \) is an isomorphism. This map is graded under the \( E \)-gradation and is a filtered isomorphism under the order filtration, in the sense that \( \theta[\delta^{-2}] \) maps \( \text{ord}^n \mathcal{J}[\delta^{-2}] \) isomorphically to \( \text{ord}^n N[\delta^{-2}] \) for each \( n \).

**Proof.** (1) By (2.3.2) \( B_{k,k-1}[\delta^{-2}] = eH_{k,k-1}[\delta^{-2}]e = e(D(h^{\text{reg}}) * W)e \), for any \( k \in C \). Repeated application of this shows that \( B_{ij}[\delta^{-2}] = e(D(h^{\text{reg}}) * W)e \) and hence, by Corollary 3.13, that \( N[\delta^{-2}] = e(D(h^{\text{reg}}) * W)eH_c = e(D(h^{\text{reg}}) * W) \). Since \( \text{ord}(\delta^2) = 0 \), we deduce that \( (\text{ogr}N)[\delta^{-2}] = e(C[h^{\text{reg}} \oplus h^*] * W) \). On the other hand, since \( \delta^{2k} \in J^k \delta^k \subseteq C[h \oplus h^*] \), certainly \( J[\delta^{-2}] = eC[h^{\text{reg}} \oplus h^*] = e(C[h^{\text{reg}} \oplus h^*] * W) \). Since \( \Theta \) is given by inclusion, \( \Theta[\delta^{-2}] \) is therefore an isomorphism.

(2) By Lemma 6.15, \( \theta \) and hence \( \theta[\delta^{-2}] \) are graded maps under the \( E \)-gradation and filtered under the order filtration. Since \( \text{gr}(\theta[\delta^{-2}]) = \Theta[\delta^{-2}] \) is an isomorphism, necessarily \( \theta[\delta^{-2}] \) is a filtered isomorphism. □

6.17. **Notation.** As in (6.15), set \( \mathcal{J} = eJ^k \delta^k, N = N(k) \) and write \( \theta(\mathcal{J})^m = \text{ord}^m \theta(\mathcal{J}) = \theta(\mathcal{J}) \cap N^m \) for all \( m \geq 0 \). We rewrite the \( C[h]W \)-basis of \( \theta(\mathcal{J}) \) constructed in the proof of Lemma 6.15 as \( \{ a_{gm} \} \), where
each \( a_{g\ell m} \) is \( g \)-homogeneous under the \( \mathbf{E} \)-gradation and has order exactly \( \ell \). Since these were induced from the bases \( \{ a_{c\ell} \} \) of \( \text{ogr}^c \mathcal{J} \), the set \( \{ a_{g\ell m} : \ell \leq t \} \) does give a basis of \( \theta(\mathcal{J})^t \).

By Lemma 6.11(2), \( \mathcal{N} \) is a free \( \mathbb{C}[\mathfrak{h}]^W \)-module and it is certainly graded. Thus, by Theorem A.1, it is graded-free. We may therefore pick a \( \mathbb{C}[\mathfrak{h}]^W \)-basis \( \{ b_{gu} \} \) of \( \mathcal{N} \) where, again, each \( b_{gu} \) is \( \mathbf{E} \)-homogeneous of degree \( g \) but of unspecified order. This basis is far from unique and one cannot expect that \( \{ b_{gu} : b_{gu} \in \mathcal{N}^m \} \) forms a basis of \( \mathcal{N}^m \); indeed at this stage we do not even know that \( \mathcal{N}^m \) is a free \( \mathbb{C}[\mathfrak{h}]^W \)-module.

6.18. We are now ready to put these observations together to prove the hard part of Proposition 6.5.

**Proposition.** Fix \( k \geq 0 \) and set \( \mathcal{J} = eJ^k \delta^k \) and \( \mathcal{N} = \mathcal{N}(k) \). Then the map \( \theta : \mathcal{J} \to \mathcal{N} \) is an isomorphism.

**Proof.** Set \( \mathfrak{m} = \mathbb{C}[\mathfrak{h}]^W \) and note that \( \mathcal{N}/\mathfrak{m}\mathcal{N} = \mathbb{C}(k) \). On the other hand, in the notation of Corollary 4.13, \( \mathcal{J}/\mathfrak{m}\mathcal{J} \iso \mathcal{J}^c[K] \) is the shift of \( \mathcal{J}^c \) by \( \deg \delta^k = K = kn(n - 1)/2 \). By Corollaries 4.13 and 6.14, we therefore have an equality of Poincaré series under the \( \mathbf{E} \)-gradation:

\[
(6.18.1) \quad p(\mathcal{J}/\mathfrak{m}\mathcal{J}, v) = v^K \frac{\sum_{\mu} f(1) f(v^{-1}) v^{-k(n(\mu) - n(\mu'))} [n]_v!}{\prod_{i=2}^n (1 - v^{-i})} = p(\mathcal{N}/\mathfrak{m}\mathcal{N}, v).
\]

Keep the \( \mathbb{C}[\mathfrak{h}]^W \)-bases of \( \theta(\mathcal{J}) \iso \mathcal{J} \) and \( \mathcal{N} \) described in Notation 6.17. We write \( a(\mathfrak{g}\mathfrak{l}m) = g \) whenever \( a_{g\ell m} \) exists for that choice of \( g, \ell, m \); thus \( \sum_{g\ell m} v^a(\mathfrak{g}\mathfrak{l}m) \) denotes the sum \( \sum v^g \), where one has one copy of \( v^g \) for each \( \ell, m \) for which \( a_{g\ell m} \) exists. Define \( b(\mathfrak{g}u) \) analogously. Since the bases \( \{ a_{g\ell m} \} \) and \( \{ b_{gu} \} \) induce \( \mathbb{C} \)-bases of \( \mathcal{J}/\mathfrak{m}\mathcal{J} \), respectively \( \mathcal{N}(k) \), (6.18.1) can be reinterpreted as

\[
(6.18.2) \quad \sum_{g\ell m} v^a(\mathfrak{g}\ell m) = v^K \frac{\sum_{\mu} f(1) f(v^{-1}) v^{-k(n(\mu) - n(\mu'))} [n]_v!}{\prod_{i=2}^n (1 - v^{-i})} = \sum_{g, u} v^b(\mathfrak{g}u).
\]

We note that (6.18.2) has several consequences for the \( a(\mathfrak{g}\ell m) \) and \( b(\mathfrak{g}u) \).

1. For fixed \( g \), there exist only finitely many elements \( a_{g\ell m} \) and \( b_{gu} \). This is because the middle expression in (6.18.2) is a well-defined series.

2. There exists a universal upper bound \( a(\mathfrak{g}\ell m) \leq T \). This is because the numerator in the middle expression in (6.18.2) is a finite sum of polynomials. However, there is no universal lower bound.

3. For any \( g_0 \), the number of \( a_{g\ell m} \) with \( g = g_0 \) equals the number of \( b_{gu} \) with \( g = g_0 \). This is simply because \( \sum v^a(\mathfrak{g}\ell m) = \sum v^b(\mathfrak{g}u) \) and the numbers are finite by (1).

We aim to adjust the basis \( \{ b_{gu} \} \) to be equal to the basis \( \{ a_{g\ell m} \} \), and we achieve this by a downwards induction on \( g \). The induction starts since, by (3), there are no basis elements \( b_{gu} \) with \( g > T \).

Let \( -\infty < G \leq T \) and, by induction, suppose that \( \{ b_{gu} : u \in \mathbb{Z} \} = \{ a_{g\ell m} : \ell, m \in \mathbb{Z} \} \) for all \( g > G \).

Suppose that there exists a basis element \( b_{Gw} \notin \{ a_{G\ell m} \} \). By Lemma 6.16(2), \( \theta(\mathcal{J})[\delta^{-2}] = \mathcal{N}[\delta^{-2}] \) and so there exists a homogeneous element \( x^m \in \mathbb{C}[\mathfrak{h}]^W \) of \( \mathbf{E} \)-degree \( m \) such that \( x^m b_{Gw} \in \theta(\mathcal{J}) \). Thus we have the \( \mathbf{E} \)-homogeneous equation

\[
(6.18.3) \quad x^m b_{Gw} = \sum_{g < G} c_{gf h} a_{gf h} + \sum c_{Gf h} a_{Gf h} + \sum_{g > G} c'_{g z} b_{gz},
\]
where \( c_{gfh}, c'_{g'} \in \mathbb{C}[h]^W \) and summation over \( f, h, z \) is suppressed. Since \( \theta(\mathcal{J}) \subseteq \mathcal{N} \), we may write each \( a_{gfh} \) as an \( \mathcal{E} \)-homogeneous sum \( a_{gfh} = \sum d_{buz} \) for some \( d_{buz} = d_{fghuz} \in \mathbb{C}[h]^W \) and obtain

\[
(6.18.4) \quad x^m b_{Gw} = \sum_{g < G} c_{gfh} d_{buz} + \sum_{g > G} c_{gfh} d_{buz} + \sum_{g > G} c'_{g'} b_{gz}.
\]

Both the last two displayed equations are \( \mathcal{E} \)-homogeneous of \( \mathcal{E} \)-degree \( G + m \) and so, by (6.18.3), each element \( c_{gfh} \) must have \( \mathcal{E} \)-degree \( \geq m \). Thus the \( b_{uz} \) appearing in the first two terms on the right hand side of (6.18.4) must have \( \mathcal{E} \)-degree \( \leq G \). Thus the only appearance of \( b_{gz} \) with \( g > G \) is in the third sum. Since the \( b_{uz} \) are a \( \mathbb{C}[h]^W \)-basis of \( \mathcal{N} \), that third term \( \sum_{g > G} c'_{g'} b_{gz} \) is actually zero.

Now consider where the specific term \( b_{Gw} \) appears on the right hand side of (6.18.4). For \( g < G \), (6.18.3) implies that \( \mathcal{E} \)-deg \( c_{gfh} \) \( > m \) for each \( f, h \) and so \( b_{Gw} \) cannot appear in the first sum. Thus it must appear nontrivially in some term \( c_{gfh'} d' b_{Gw} \) in the second sum. In this case, (6.18.3) implies that \( \mathcal{E} \)-deg \( c_{gfh'} = m \). Hence \( d' \in \mathbb{C} \setminus \{0\} \) and

\[
a_{G fh'} = d' b_{Gw} + \sum_{(uz) \neq (Gw)} d''_{uz} b_{uz}.
\]

Thus we can replace \( b_{Gw} \) by \( a_{G fh'} \) in our basis for \( \mathcal{N} \). By (3), the sets \( \{a_{Glm} : \ell, m \in \mathbb{Z}\} \) and \( \{b_{Gu} : u \in \mathbb{Z}\} \) have equal finite cardinality. After a finite number of steps we therefore have \( \{b_{Gu}\} \subseteq \{a_{Glm}\} \) and hence \( \{b_{Gu}\} = \{a_{Glm}\} \). This completes the inductive step and hence the proof of the lemma.

We can now pull everything together and prove both Theorem 6.4 and Proposition 6.5.

6.19. **Proof of Proposition 6.5.** Recall from Lemma 6.9 that \( \Theta : eJ^k \delta^k \to \text{ogr} N(k) \) is the natural inclusion. On the other hand, for any \( k \geq 0 \), Proposition 6.18 implies that the map \( \theta : eJ^k \delta^k \to N(k) \) is an isomorphism. Lemma 6.15(2) therefore implies that \( \text{gr}_A N(k) = \text{ogr} \theta(eJ^k \delta^k) = \Theta(eJ^k \delta^k) = eJ^k \delta^k \).

6.20. **Proof of Theorem 6.4.** (1) This is immediate from Corollary 3.13(1) and Lemma 5.5.

(2) Fix \( i \geq j \geq 0 \). Since \( e + j \) still satisfies Hypothesis 6.2, Proposition 6.5 implies that \( \text{ogr} B_{ij} eH_{c+j} = eJ^{i-j} \delta^{i-j} \). Multiplying this identity on the right by \( e \) and applying Lemma 6.8 and Corollary 3.13(1) gives

\[
eJ^{i-j} \delta^{i-j} e = \text{ogr}(B_{ij} eH_{c+j})e = \text{ogr}(B_{ij} eH_{c+j})e = \text{ogr} B_{ij}.
\]

Since \( \delta \) transforms under \( W \) by the sign representation, Lemma 4.4(1) shows that \( eJ^{i-j} \delta^{i-j} e = eA^{i-j} \delta^{i-j} e \). Combining these observations gives \( \text{ogr} B_{ij} = eA^{i-j} \delta^{i-j} e \). Therefore, \( \text{ogr} B = \bigoplus \text{ogr} B_{ij} = e\hat{A}e \cong \hat{A} \), as graded vector spaces. In order to ensure that this is an isomorphism of graded \( \mathbb{Z} \)-algebras we need to check that the multiplication in \( \text{ogr} B \) coming from the tensor product multiplication in \( B \) is the same as the natural multiplication in \( \hat{A} \). This follows from Lemma 6.7(1).

(3) The equivalences \( \text{ogr}(B) - \text{qgr} \cong A - \text{qgr} \cong \text{Coh}((Hilb(n)) \) follow from (2) combined with (5.3), respectively Corollary 4.10(1).
6.21. **Corollary.** Assume that $c \in \mathbb{C}$ satisfies Hypothesis 6.2 and pick $i \geq j \geq 0$. Then, for $m \geq 0$, each of the modules $\text{ord}^m N(i)$, $\text{ogr}^m N(i)$, $\text{ord}^m B_{ij}$ and $\text{ogr}^m B_{ij}$ is free as a left $\mathbb{C}[\hbar]^W$-module.

**Proof.** By construction and Proposition 6.5, the map $\Theta : \text{ogr} N(i) \to eJ^i \delta^i$ is an isomorphism of $\text{ord}$-graded modules. Thus $\text{ogr}^m N(i) \cong \text{ogr}^m eJ^i \delta^i$ is a free $\mathbb{C}[\hbar]^W$-module by Lemma 4.9. By induction on $m$, it follows that $\text{ord}^m N(i)$ is also free. The analogous results for $B_{ij}$ follow by multiplying everything on the right by $e$. □

6.22. We end the section by noting that Proposition 6.5 provides an interesting connection between $H_c$-modules and the isospectral scheme $X_n$ defined in (4.10). Adjusting to the conventions of this section, we identify $\text{Hilb}(n) = \text{Proj} \tilde{A}$, for $\tilde{A} = \bigoplus A^k \delta^k$. By construction, the Procesi bundle $P = \rho_* \mathcal{O}_{X_n}$ from (4.10) is then just the image in $\text{Coh} \text{Hilb}(n)$ of the $\tilde{A}$-module $\bigoplus J^k \delta^k$. Thus the next result is an immediate consequence of Proposition 6.5.

**Corollary.** Assume that $c \in \mathbb{C}$ satisfies Hypothesis 6.2. Let $e\tilde{H}_c = \bigoplus_{k \geq 0} B_{k0} \otimes_{U_c} e\tilde{H}_c$ be the $B$-module associated to the $U_c$-module $eH_c$ and filter each $B_{k0} \otimes_{U_c} eH_c \cong B_{k0} eH_c$ by the $\text{ord}$ filtration. Set $\text{ogr} e\tilde{H}_c = \bigoplus \text{ogr} B_{k0} eH_c$. Then the sheaf associated to $\text{ogr} e\tilde{H}_c$ in $\text{Coh} \text{Hilb}(n)$ is the Procesi bundle $\mathcal{P}$. □

6.23. Just as Theorem 6.4 can be interpreted as saying that $U_c$ provides a noncommutative model for $\text{Hilb}(n)$, so Corollary 6.22 can be interpreted as saying that the algebra $H_c$ provides a noncommutative model for $X_n$. Here is one aspect of this analogy. It follows from [BKR] and [Ha4] that there is an equivalence $\xi$ of derived categories between $\mathfrak{h} \oplus \mathfrak{h}^*/W$ and $\text{Hilb}(n)$ that is induced by a Fourier-Mukai transform over $\mathcal{P}$. Now pass to the noncommutative situation, replacing $\mathfrak{h} \oplus \mathfrak{h}^*/W$, $\text{Hilb}(n)$ and $\mathcal{P}$ by $H_c\text{-mod}$, $B\text{-qgr}$ and $eH_c$, respectively. Then Corollary 3.13 shows that $eH_c$ still induces a derived equivalence between the two categories. Indeed, it is even an equivalence of categories. The fact that derived equivalences in the commutative case can become full equivalences in the noncommutative case happens elsewhere and is in accord with the philosophy behind [GK, Conjecture 1.6] (see [GK, Remark 1.7]).

As will be justified in [GS], Corollary 6.22 therefore “sees” the equivalence $\xi$ and this provides some intriguing connections between sheaves on $\text{Hilb}(n)$ and modules over $H_c$.

6.24. If one considers Cherednik algebras in characteristic $p > 0$, where $H_c$ is a finite module over its centre, then the relationship between $H_c$ and $\text{Hilb}(n)$ becomes closer still. For example, [BFG] shows that there is even a derived equivalence between $H_c$ and an Azumaya algebra over a Frobenius twist of $\text{Hilb}(n)$. Similarly in characteristic zero, symplectic reflection algebras with parameter $t = 0$ are finite modules over their centre, and [GSm, Theorem 1.2] shows that there are often derived equivalences between these algebras and varieties that deform Hilbert schemes.

7. **Tensor product filtrations**
7.1. The tensor product decomposition (6.3.2) of the \( B_{ij} \) can be used to give a second filtration on that module by inducing a filtration on \( B_{ij} \) from the ord filtration on the tensorands. It turns out that the main theorem is essentially equivalence to the assertion that the two filtrations are equal. In this short section we give the details behind this assertion. Analogues of this result also hold for the module \( N(k) \) defined in (6.5) and the module \( M(k) = H_{c+k} e B_{k0} = H_{c+k} \delta e B_{k-1,0} \) defined in (B.1) and so we begin by giving a general context for all three results.

7.2. For fixed \( i \geq j \geq 0 \) we are interested in the following tensor product decompositions

\[
B_{ij} \cong Q^{c+i}_{c+i-1} \otimes Q^{c+i-1}_{c+i-2} \otimes \cdots \otimes Q^{c+j+1}_{c+j},
\]

(7.2.2)

\[
N(i) \cong Q^{c+i}_{c+i-1} \otimes \cdots \otimes Q^{c+1}_c \otimes eH_c \quad \text{or} \quad N(i) \cong B_{i0} \otimes eH_c
\]

and

\[
M(i) \cong H_{c+i} \delta e \otimes U_{c-i-1} B_{c-i-2} \otimes \cdots \otimes U_{c+1} B_{10} \quad \text{or} \quad M(i) \cong H_{c+i} \delta e \otimes U_{c+i-1} B_{i-1,0}
\]

(7.2.3)

where the tensor products are over the appropriate rings \( U_k \). Corresponding to these decompositions we have the tensor product filtration \( \text{ten} \) defined by the following convention: Given a module \( C = C_1 \otimes \cdots \otimes C_r \), where each \( C_j \) is filtered by the ord filtration, define

\[
\text{ten}^n(C) = \left\{ \sum c_1 \otimes \cdots \otimes c_r, \text{ where } c_m \in \text{ord}^{\ell(m)}(C_m) \text{ with } \sum_{m=1}^r \ell(m) \leq n \right\}.
\]

(7.2.4)

As usual, we will write the associated graded module as \( \text{tgr} \, C = \bigoplus \text{ten}^n \, C / \text{ten}^{n-1} \, C \).

**Lemma.** Assume that \( c \in \mathbb{C} \) satisfies Hypothesis 6.2. Let \( C \) denote one of the objects \( B_{ij} \), \( N(i) \) or \( M(i) \) and consider the tensor product filtrations induced from one of the tensor product decompositions (7.2.1–7.2.3). Then \( \text{ord}^m \, C = \text{ten}^m \, C \), for all \( m \geq 0 \).

**Proof.** We will prove the result for the decomposition (7.2.1) and the first decomposition in each of (7.2.2) and (7.2.3). The proof in the remaining cases is left to the reader as it uses essentially the same argument, although one needs to use the conclusion of the lemma for (7.2.1).

In each of the three cases we are given a decomposition \( C = C_1 \otimes \cdots \otimes C_r \), say with \( \text{ogr} \, C_j = D_j \) and \( \text{ogr} \, C = D \). Moreover, by Theorem 6.4, respectively Proposition 6.5 combined with Lemma 6.9, respectively Proposition B.1 combined with Lemma B.2, there is an equality \( D_1 \cdots D_r = D \) given by multiplication in \( D(\text{reg}) \ast W \). Equivalently, the natural multiplication map \( \chi : D_1 \otimes \cdots \otimes D_r \to D \) is surjective. Consider the graded map \( \chi \) in more detail. Given elements \( \bar{\alpha}_j \in \text{ogr}^m(j) \, D_j \), with \( m = \sum m(j) \), lift the \( \bar{\alpha}_j \) to elements \( \alpha_j \in \text{ord}^m(j) \, C_j \). Then \( \chi \) is defined by

\[
\chi(\bar{\alpha}_1 \otimes \cdots \otimes \bar{\alpha}_r) = (\alpha_1 \cdots \alpha_r + \text{ord}^{m-1} \, C) / \text{ord}^{m-1} \, C.
\]
By the definition of the ten filtration, this says that image of $\chi$ is contained in (and indeed equal to) $\bigoplus_m (\text{ten}^m C + \text{ord}^{m-1} C) / \text{ord}^{m-1} C$. But $\chi$ is surjective. By induction on $m$ we therefore have $\text{ord}^m C = \text{ten}^m C + \text{ord}^{m-1} C = \text{ten}^m C$.

7.3. The equality of filtrations given by Lemma 7.2 is not merely a formality; indeed the result for $B_{ij}$ is essentially the same result as Theorem 6.4. To see this, suppose that $\text{ogr} B_{ij} = \text{tgr} B_{ij}$ for all $i \geq j \geq 0$. As Lemma 6.9(2) shows, $\text{ogr} B_{i+1,\ell} = A^1\delta$ for each $\ell$ and so, by Lemma 6.7(2), we get a surjection $\chi$ from $E = (A^1\delta)^{\otimes(i-j)}$ onto $\text{tgr} B_{ij} = \text{ogr} B_{ij}$.

The multiplication map $\phi : E \to (A^1\delta)^{i-j}$ is surjective and its kernel is the largest torsion $A^0$-submodule of $(A^1\delta)^{i-j}$. On the other hand $\text{ogr} B_{ij} \subseteq e\mathbb{C}[\mathfrak{h} \oplus \mathfrak{h}^*]^W$ is a torsion-free $A^0$-module and so $\ker(\phi) \subseteq \ker(\chi)$. Thus $\text{ogr} B_{ij} = E / \ker(\chi)$ is a homomorphic image of $(A^1\delta)^{i-j}$. Since $(A^1\delta)^{i-j}$ is a right ideal of the domain $A^0$, any proper factor of $(A^1\delta)^{i-j}$ will be torsion. Thus $\ker(\phi) = \ker(\chi)$ and $\text{ogr} B_{ij} \cong (A^1\delta)^{i-j}$.

7.4. The observation in (7.3) suggests that Lemma 7.2 will only hold for very special decompositions and this is indeed the case. In essence, Theorem 6.4 says that the identity $B_{ij} \cong B_{i,j-1} \otimes \cdots \otimes B_{j+1,j}$ is a filtered isomorphism. On the other hand, an identity like $\text{ogr} B_{ij} \subseteq e\mathbb{C}[\mathfrak{h} \oplus \mathfrak{h}^*]^W$ is a torsion-free $A^0$-module and so $\ker(\phi) \subseteq \ker(\chi)$. Thus $\ker(\phi) = \ker(\chi)$ and $\text{ogr} B_{ij} \cong (A^1\delta)^{i-j}$.

As a second example, it is easy to check that Lemma 7.2 will fail for $M(i)$ if one introduces one more tensor product, $M(i) \cong H_{c+1,\ell} \otimes_{U_{c+1}} B_0$. Indeed, Lemma B.2 implies that $\text{ogr} M(1) = \mathbb{C}[\mathfrak{h} \oplus \mathfrak{h}^*]e$. On the other hand, for the given decomposition Lemmas 6.9 and 6.7 imply that $\text{tgr} H_{c+1} \otimes_{U_{c+1}} \text{ogr} Q_{c+1}^+ \cong \mathbb{C}[\mathfrak{h} \oplus \mathfrak{h}^*]e \otimes_{A^0} A^1\delta e$. Clearly the image of $T$ in $\text{ogr} M(1)$ is just $\mathbb{C}[\mathfrak{h} \oplus \mathfrak{h}^*]eA^1\delta e = J^1\delta e$. By the argument of the second paragraph of (7.3), this is also the image of $\text{tgr} M(1)$ in $\text{ogr} M(1)$.

APPENDIX A. Graded projective modules

A.1. The aim of this appendix is to prove the following graded analogue of a well-know result of Kaplansky [Ka, Theorem 2], for which we do not know a reference.

**Theorem.** Let $A = \bigoplus_{i \geq 0} A_i$ be a connected $\mathbb{N}$-graded $k$-algebra (thus $A_0 = k$). Let $P$ be a right $A$-module that is both graded and projective. Then $P$ is a graded-free $A$-module in the sense that $P$ has a free basis of homogeneous elements.

**Proof.** Throughout this proof all graded maps are graded maps of degree zero. We will write the degree of a homogeneous element $x \in P$ as $|x|$. 39
An observation of Eilenberg [Ei, Section 1] shows that $P$ is graded projective in the sense that there is a graded isomorphism $F \cong P \oplus Q$, for some $A$-module $Q$ and graded-free $A$-module $F$. We need a minor variant on this result, so we give the proof. Take a graded surjection $\phi : F = \bigoplus f_i A \twoheadrightarrow P$ and an ungraded splitting $\theta : P \to F$. If $p_i = \phi(f_i)$, then write $\theta(p_i) = g_i + h_i$, where $g_i$ is the homogeneous component of $\theta(p_i)$ with $|g_i| = |p_i|$. Then check that the map $p_i \mapsto g_i$ also splits $\phi$. This proof also shows that, if $P$ is countably generated, then we can take $F$ to be a countably generated graded-free module.

The heart of the proof of the theorem is contained in the next two sublemmas.

**A.2. Sublemma.** Under the hypotheses of the theorem, $P$ is a graded direct sum of countably generated $A$-modules.

**Proof.** The proof of [Ka, Theorem 1] also works in the category of graded modules. \qed

**A.3. Sublemma.** Keep the hypotheses of the theorem and assume that $P$ is countably generated. If $x \in P$ then there exists a graded-free direct summand $G$ of $P$ such that $x \in G$.

**Proof.** By the result of Eilenberg described above, we may pick a graded isomorphism $F \cong P \oplus Q$, for some $A$-module $Q$ and countably generated graded-free $A$-module $F$. Select a homogeneous basis $\{u_i : i \in \mathbb{N}\}$ for $F$ such that there is a graded expression $x = \sum_{i=1}^{n} u_i a_i$, with $a_i \in A$ and $n$ as small as possible.

We first claim that no $a_j$ can be written as a left linear combination of the other $a_i$. Indeed, suppose that $a_n = \sum_{i=1}^{n-1} r_i a_i$, for some $r_i \in A$. By taking the appropriate component we may assume that each $r_i$ is homogeneous with $|r_i| = |a_n| - |a_i|$. It follows that $|u_n r_i| = |u_i|$ and hence that $u_i' = u_i + u_n r_i$ is homogeneous. However

$$\sum_{i=1}^{n-1} u_i' a_i = \sum_{i=1}^{n-1} u_i a_i + u_n (\sum_{i=1}^{n-1} r_i a_i) = x.$$  

This contradicts the minimality of $n$ and proves the claim.

Reorder the basis $\{u_i\}$ so that $|u_i| \leq |u_{i+1}|$ for $1 \leq i \leq n$ and write $u_i = p_i + q_i$, for $p_i \in P$, $q_i \in Q$, all of the same degree. Notice that $P \ni x = \sum u_i a_i = \sum p_i a_i + \sum q_i a_i$ and so $\sum q_i a_i \in P \cap Q = 0$. Hence

(A.3.1) \[ x = \sum_{i=1}^{n} u_i a_i = \sum_{i=1}^{n} p_i a_i \]

Next write each $p_i$ as a homogeneous sum $p_i = \sum_{j=1}^{n} u_j c_{ji} + t_i$, where $t_i \in \sum_{i > n} u_i A$. Then

$$x = \sum_{i=1}^{n} u_i a_i = \sum_{i=1}^{n} p_i a_i = \sum_{i=1}^{n} u_j c_{ji} a_i + \sum_{i=1}^{n} t_i a_i.$$  

Since $\{u_i\}$ is a basis,

(A.3.2) \[ a_j = \sum_{i=1}^{n} c_{ji} a_i \quad \text{for} \quad 1 \leq j \leq n. \]

We claim that $c_{ji} = 0$ for $i < j$ and that $|c_{ji}| > 0$ whenever $i > j$ (and $c_{ji} \neq 0$). Since $|u_i| \leq |u_{i+1}|$, we have $|a_i| \geq |a_{i+1}|$ for each $i$. Also $|c_{ji}| = |u_i| - |u_j|$ for all $i, j$ and so $c_{ji} = 0$ if $|u_i| < |u_j|$. Thus both parts
of the claim are clear when \(|u_i| \neq |u_j|\); equivalently, when \(|a_i| \neq |a_j|\). So, suppose that \(|a_i| = |a_j|\), for some \(i \neq j\) and that \(c_{ji} \neq 0\). Then \(c_{ji} \in k^*\) and so (A.3.2) expresses \(a_i\) as a left linear combination of the other \(a_{\ell}\). This contradicts the initial minimality assumption on \(n\) and proves the claim. Note that \(c_{jj} = 1\) for all \(j\), since otherwise (A.3.2) would express \(a_j\) as a left linear combination of the other \(a_{\ell}\).

The last paragraph implies that \(C = (c_{ji})\) is an upper triangular matrix, with units on the diagonal and so it is invertible. In particular, \(\{p_1, \ldots, p_n\} \cup \{u_{n+\ell} : \ell > 0\}\) is a basis for \(F\). Thus \(G = \sum_{i=1}^n p_i A\) is a graded-free direct summand of \(F\) contained in \(P\). Thus \(G\) is also a graded-free direct summand of \(P\) which, by (A.3.1), contains \(x\).

A.4. The proof of the theorem follows from the sublemmas by an easy induction. By Sublemma A.2 we may assume that \(P\) is countably generated, say by homogeneous elements \(z_i\) for \(i \in \mathbb{N}\). By induction, suppose that there is a graded decomposition \(P = Q_1 \oplus \cdots \oplus Q_n \oplus R_n\), where each \(Q_i\) is graded-free and \(z_i \in Q_1 \oplus \cdots \oplus Q_i\), for \(1 \leq i \leq n\). By Sublemma A.3 this does hold when \(n = 1\). Write \(z_{n+1} = q + r\) as a homogeneous sum, where \(q \in \sum Q_j\) and \(r \in R_n\). Since \(R_n\) also satisfies the hypotheses of Sublemma A.3, \(R_n\) has a graded-free summand \(Q_{n+1}\) containing \(r\), completing the inductive step. Finally,

\[\bar{P} = \lim_{n \to \infty} (Q_1 \oplus \cdots \oplus Q_n) \cong \bigoplus_{i=1}^\infty Q_i\]

is a graded-free submodule of \(P\) that contains each \(z_i\). Therefore \(P = \bar{P}\).  

\[\square\]

**Appendix B. Another module**

B.1. Fix \(c \in \mathbb{C}\) that satisfies Hypothesis 6.2 and an integer \(k \geq 0\). For applications in [GS] we will need an analogue of Proposition 6.5 for the left \(H_{c+k}\)-module \(M(k) = H_{c+k}eB_{k0} \subseteq D(h^{reg}) \ast W\). As before, we filter \(M(k)\) by the induced order filtration \(\text{ord}\), so that \(\text{ogr} M(k) \subseteq \text{ogr} D(h^{reg}) \ast W = \mathbb{C}[h^{reg} \oplus h^*] \ast W\). The aim of this appendix is then to prove:

**Proposition.** The left \(H_{c+k}\)-module \(M(k) = H_{c+k}eB_{k0}\) satisfies \(\text{ogr} M(k) = J^{k-1} \delta^k c\).

Recall that Proposition 6.5 showed that the module \(N(k) = B_{k0} \otimes eH_c\) had associated graded ring \(eJ^k \delta^k\). In a sense, Proposition B.1 is just a left-right analogue of that result and so much of the present proof is formally very similar to that of Proposition 6.5.

We should first explain why the two results involve different powers of \(J^1\). The reason is that one can write \(M(k) = H_{c+k} \delta eB_{k-1,0}\). By Corollary 3.13 and (3.3.2) the left hand end of this expression collapses to give \(M(k) = H_{c+k} \delta eB_{k-1,0}\). In particular, \(M(1) = H_{c+1} \delta e\). A routine computation using Lemmas 6.7 and 6.8 then gives:

**B.2. Lemma.** \(\text{ogr} M(1) = \mathbb{C}[h \oplus h^*] \delta e\) while \(J^{k-1} \delta^k c \subseteq \text{ogr} M(k)\) for all \(k \geq 1\).  

\[\square\]
It takes considerably more work to show that \( J^{k-1}\delta^k e \) actually equals \( \text{ogr} M(k) \) for \( k > 1 \). The proofs of the first few steps in this argument are very similar to those of Lemmas 6.11, 6.15 and 6.16 in the proof of Proposition 6.5 and so we will just indicate how to modify the earlier proofs to work here.

B.3. Since \( M(k) \) is a \((H_{c+k}, U_c)\)-bimodule, the embeddings \( \mathbb{C}[\mathfrak{h}] \hookrightarrow H_{c+k} \) and \( \mathbb{C}[\mathfrak{h}^*]^W \hookrightarrow U_c \) make \( M(k) \) into a \((\mathbb{C}[\mathfrak{h}], \mathbb{C}[\mathfrak{h}^*]^W)\)-bimodule. Let \( \mathbb{C} \) be the trivial module over either \( \mathbb{C}[\mathfrak{h}] \) or \( \mathbb{C}[\mathfrak{h}^*]^W \) and set \( \overline{M(k)} = \mathbb{C} \otimes_{\mathbb{C}[\mathfrak{h}]} M(k) \) and \( M(k) = M(k) \otimes_{\mathbb{C}[\mathfrak{h}^*]^W} \mathbb{C} \).

**Lemma.** (1) \( M(k) \) is free as a left \( \mathbb{C}[\mathfrak{h}]-\)module and a right \( \mathbb{C}[\mathfrak{h}^*]^W \)-module.

(2) \( M(k) \) is a finitely generated, free left \( \mathbb{C}[\mathfrak{h}]-\)module.

(3) Analogously, \( \overline{M(k)} \) is a finitely generated, free right \( \mathbb{C}[\mathfrak{h}^*]^W \)-module.

**Proof.** (1) By Corollary 3.13, \( M(k) \) is projective as a left \( H_{c+k} \)-module and as a right \( U_c \)-module. By (2.2.1), \( H_{c+k} \) and hence \( M(k) \) is free as a left \( \mathbb{C}[\mathfrak{h}]-\)module. Similarly, the argument of Lemma 6.11(2) shows that \( U_c \) and hence \( M(k) \) are free right \( \mathbb{C}[\mathfrak{h}^*]^W \)-modules.

(2) This is contained in the proof of Lemma 6.11(3).

(3) Mimic the proof of Lemma 6.11(4). \( \square \)

B.4. Using the conventions from (6.14), each \( M(k) \) and \( J^{k-1}\delta^k e \) is \( \mathfrak{E} \)-graded. Since \( \mathbb{C}[\mathfrak{h}]_+ \) is \( \mathfrak{E} \)-graded, the \( \mathfrak{E} \)-grading on \( M(k) \) descends to one on \( \overline{M(k)} \). Similarly, \( J^{k-1}\delta^k e \) has the order grading \( \text{ogr} \) from (6.15).

Write \( \Theta : J^{k-1}\delta^k e \hookrightarrow \text{ogr} M(k) \) for the inclusion from Lemma B.2.

**Lemma.** There exists an injective map \( \theta : J^{k-1}\delta^k e \hookrightarrow M(k) \) of left \( \mathbb{C}[\mathfrak{h}] \)-modules such that:

(1) \( \theta \) is an \( \mathfrak{E} \)-graded homomorphism and is a filtered homomorphism under the order filtration.

(2) The associated graded map \( \text{ogr} \theta : J^{k-1}\delta^k e \rightarrow \text{ogr} M(k) \) induced by \( \theta \) is precisely \( \text{ogr} \theta = \Theta \).

(3) In the notation of (6.16), the inclusion \( \theta(\delta^{-2}) : (J^{k-1}\delta^k e)(\delta^{-2}) \rightarrow M(k)(\delta^{-2}) \) is an isomorphism. This map is \( \mathfrak{E} \)-graded and is a filtered isomorphism under the order filtration.

**Proof.** (1,2) As in the proof of Lemma 6.15, one constructs \( \theta \) by lifting a \( \mathfrak{E} \)-homogeneous basis of the free \( \mathbb{C}[\mathfrak{h}] \)-module \( \text{ogr}^n(J^{k-1}\delta^k)e \) to a set of \( \mathfrak{E} \)-homogeneous elements in \( \text{ord}^n M(k) \).

(3) This is essentially the same as the proof of Lemma 6.16. \( \square \)

B.5. By Lemma 6.10, \( M(k) \) is graded under the adjoint \( \mathfrak{h} \)-action and, as both copies of \( \mathbb{C} \) are \( \mathfrak{h} \)-graded modules, this grading restricts to one on \( \overline{M(k)} \) and \( M(k) \). In each case, we call this the \( \mathfrak{h} \)-grading. For the reasons given in (6.14), this does not equal the \( \mathfrak{E} \)-grading.

**Proposition.** If \( \overline{M(k)} \) is graded via the adjoint \( \mathfrak{h} \) action, then it has Poincaré series

\[
p(M(k), v) = \frac{\sum_{\mu} f_\mu(1)f_{\mu}(v^{-1})u^{-(k-1)(n(\mu)-n(\mu'))}}{\prod_{i=2}(1 - v^{-i})}.
\]

42
Proof. This is similar to the proof of Proposition 6.13 except that we use the module \( Y = H_e \otimes_R \mathbb{C} \), where \( R = e \mathbb{C}[h^*]^W \mathbb{C} \), in place of \( X = H_e \otimes_{\mathbb{C}[h^*]} \mathbb{C} \). As in that proposition, \( Y \) is an object in \( \mathcal{O}_c \) and so we can write \( [Y] = \sum \mu p_\mu [\Delta_c(\mu)] \) for some \( p_\mu \in \mathbb{Z}[v, v^{-1}] \). To calculate the \( p_\mu \) note that, by (2.2.1), \( Y \cong \mathbb{C}[h] \otimes \mathbb{C}[h^*]^c \mathcal{W} \).

Applying \((\mathbb{C} \otimes \mathbb{C}[h])-\) to the equation \([Y] = \sum p_\mu [\Delta_c(\mu)]\) therefore yields \([\mathbb{C}[h^*]^c \mathcal{W}] = \sum p_\mu [\mu].\) Thus (3.9.1) implies that \( p_\mu = f_\mu(v^{-1}) \) (this is a polynomial in \( v^{-1} \) rather than \( v \) since \( \mathbb{C}[h^*] \) is negatively \( E \)-graded) and so, as an element of \( G_0(\mathcal{O}_c), \)

\[
(B.5.1) \quad [Y] = \sum \mu f_\mu(v^{-1})[\Delta_c(\mu)].
\]

Now consider \( M(k) \), which can be written as \( H_{c+k} \otimes_{U_{c+k}} B_{k\tilde{0}} \otimes_{U_{c}} Y \). By (3.3.2) and Corollary 3.13, \( \mathbb{C} \otimes \mathbb{C}[h] \otimes_{U_{c+k}} \mathbb{C}[h] \otimes_{U_{c}} \mathbb{C}[h] \cong \Delta_{c+k}(\lambda) \). Thus (B.5.1) and Lemma 6.12 combine to show that

\[
[M(k)] = \sum \mu f_\mu(v^{-1})v^{k(n(\mu)-n(\mu'))}[\Delta_{c+k}(\mu)].
\]

As graded vector spaces, \( \Delta_{c+k}(\mu) \cong \mathbb{C}[h] \otimes \mu \) and so \( p(\Delta_{c+k}(\mu), v) = f_\mu(1)(1-v)^{-(n-1)} \) by (3.9.2). Therefore,

\[
(B.5.2) \quad p(M(k), v) = \sum \mu f_\mu(1)f_\mu(v^{-1})v^{k(n(\mu)-n(\mu'))}(1-v)^{(n-1)}.
\]

By parts (2) and (3) of Lemma B.3, a homogeneous basis for \( M(k) \) is given by lifting a homogeneous \( \mathbb{C} \)-basis for \( \mathbb{C} \otimes \mathbb{C}[h^*]^W \mathbb{C} = \mathbb{C} \otimes \mathbb{C}[h] M(k) \). Thus, combining (B.5.2) with the formul\( e p(\mathbb{C}[h^*]^W, v) = \prod_{i=2}^{n}(1-v)^{(n-1)} \) and \( p(\mathbb{C}[h], v) = (1-v)^{n-1} \) gives

\[
(B.5.3) \quad p(M(k), v) = \sum \mu f_\mu(v^{-1})f_\mu(1)v^{k(n(\mu)-n(\mu'))}(1-v)^{n-1}.
\]

By [Op, Theorem 8] the fake degrees satisfy \( f_\mu(v^{-1}) = f_\mu'(v^{-1})v^{n(\mu')-n(\mu)}. \) Combined with (3.9.2) this implies that

\[
f_\mu(v^{-1})f_\mu(1)v^{k(n(\mu)-n(\mu'))} = f_\mu'(v^{-1})f_\mu'(1)v^{(k-1)(n(\mu')-n(\mu))}.
\]

Substituting this into (B.5.3) gives the stated formula for \( p(M(k), v) \).

\[ \square \]

B.6. As was true for Corollary 6.14, we need to slightly modify Proposition B.5 in order to compute the Poincaré series for \( M(k) \) under the \( E \)-grading.

**Corollary.** Set \( K = kn(n - 1)/2 \) and \( n = \mathbb{C}[h]_+ \). Under the \( E \)-grading there is an equality of Poincaré series

\[
(B.6.1) \quad p(M(k), v) = v^K \sum \mu f_\mu(1)f_\mu(v^{-1})v^{(k-1)(n(\mu)-n(\mu'))}(1-v)^{(n-1)} = p(\sum_{i=2}^{n}(1-v)^{n-1} k^{j-k} \delta^k/n_j k^{i-1} \delta^k, v).
\]
Proof. Equation 6.10.1 continues to hold if we replace \( e \delta e \) by \( m \delta e \). Thus the argument of Corollary 6.14(1) combined with Proposition B.5 and the formula \( M(k) = H_{c+k \delta} e B_{k-1,0} \) gives the first equality of (B.6.1).

In order to obtain the second equality in (B.6.1), note that
\[
p(v) = p(J^{k-1}/n, J^{k-1}, v)
\]
and
\[
q(v) = p(J^{k-1}/m, J^{k-1}, v),
\]
where \( m = \mathbb{C}[h]^W \). The Poincaré series \( q(v) \) has been computed in Corollary 4.13. Since that series was obtained by specialising the bigraded Poincaré series \( p(J^d, s, t) \) from Corollary 4.11, it follows immediately that
\[
p(v) = \frac{p(\mathbb{C}[h], v)}{p(\mathbb{C}[h]^W, v)} q(v) = \frac{(1 - v)^{n-1}}{\prod_{i=2}^n (1 - v^i)} q(v) = \frac{q(v)}{[n]_v!}
\]
where the final equality uses (4.13.1). Substituting these observations into Corollary 4.13 gives the second equality in (B.6.1). \( \square \)

B.7. Proof of proposition B.1. We first show that the map \( \theta : J^{k-1} \delta e \to M(k) \) is an isomorphism for all \( k \geq 1 \). This is analogue of Proposition 6.18. In that case, a purely formal argument showed that Proposition 6.18 followed from (6.18.1). The same argument can be used, essentially without change, to show that the bijectivity of \( \theta \) follows from (B.6.1).

Combined with Lemma B.4(ii) this says that \( \text{ogr} M(k) = \text{ogr} \theta(J^{k-1} \delta e) = J^{k-1} \delta e \), as required. \( \square \)
A¹, A², alternating polynomials, (4.3)(4.9) \( \mathcal{O}_c \), graded category \( \mathcal{O} \) for \( H_c \), (6.12)

\( A = \bigoplus A^i \), \( A = \bigoplus A' \), (4.3),(4.9) \([n]_v = (1 - v)^{-n} \prod_{i=1}^{n} (1 - v^i) \), (4.13)

\( \mathcal{A} = \bigoplus_{i\geq j \geq 0} A^{i-j} \), (6.4) \( N(k) = B_{\text{koe}} H_c \), (6.5)

\( B_1 \), the tautological rank \( n \) bundle, (4.5) \( \overline{N(k)} = \mathbb{C} \otimes N(k), \ N(k) = N(k) \otimes \mathbb{C} \), (6.11)

\( B = \bigoplus B_{ij} \) for \( B_{ij} = \prod_{n=1}^{i-1} Q_n^{i+1} \), (6.3) \( \text{ord, ogr}, \text{ order filtration and order gradation} \), (2.3)

\( d(\mu) = \{(i,j) \in \mathbb{N} \times \mathbb{N} : j < \mu_{i+1} \} \), (2.6) \( p(M,v) \), Poincaré series, (4.13)

\( \delta = \prod_{\alpha \in \mathbb{S}} \alpha_s \), (2.3) \( p(V,s,t) \), bigraded Poincaré series, (4.8)

\( \Delta_c(\mu) \), the standard module, (2.7) \( p(M,v,W) \), \( W \)-graded Poincaré series, (3.10)

\( \hat{\Delta}_c(\mu) \), the graded standard module, (6.12) \( qgr, Qgr \), quotient categories, (5.2)

\( \text{dominance ordering on} \ \text{Irrep}(W) \), (2.6) \( \mathbb{Q}_{c+1} = eH_{c+1} e \) \( \delta = eH_{c+1} e \) \( \delta e \), (3.2)

Dunkl-Cherednik representation \( \theta_c \), (2.3) \( \mathbb{E}(n,l) = H^0(\text{Hilb}^n \mathbb{C}^2, \mathcal{P}_1 \otimes \mathcal{B}_1) \), (4.6)

\( \mathbb{E} = \sum x_i \delta_i \), the Euler operator, (2.4) \( \rho_i : X_n \rightarrow \text{Hilb}^n \mathbb{C}^2, \ \rho : X_n \rightarrow \text{Hilb}(n) \), (4.3),(4.10)

\( \mathbb{E} \)-deg, the Euler grading, (2.4) \( S = \mathbb{S}^n, S = \mathbb{J}^n \), (4.3)(4.9)

\( e, e_\ast \), trivial and sign idempotents, (2.5) \( S_q = S_q(n,n) \), \( q \)-Schur algebra, (3.5)

fake degrees \( f_\mu \), (3.9) \( \mathcal{S}, \) the reflections in \( W \), (2.1)

\( H_c \), the rational Cherednik algebra, \( \mathfrak{h}, \mathfrak{h}^\ast \), \( \mathfrak{h}^{reg} \), (2.1) \( \sigma(r) \), the principal symbol of \( r \), (6.7)

\( \mathfrak{h} = \mathfrak{h}_c = \frac{1}{2} \sum_{i=1}^{n-1} x_i y_i + y_i x_i \in H_c \), (2.4) \( \text{sign, the sign representation of} \ W \), (2.6)

\( \text{Hecke algebra} \ H_{\mathfrak{h}} \), (2.8) \( \tau : \text{Hilb}^n \mathbb{C}^2 \rightarrow \mathbb{C}^{2^n}/W \), (4.2)

\( \text{Hilbert schemes} H^\text{reg}_c \mathbb{C}^2, \text{Hilb}(n) \), (4.2),(4.10) \( \text{triv}, \) the trivial representation of \( W \), (2.6)

\( I_\mu \), monomial ideal for a partition \( \mu \), (4.7) \( U_c = eH_c e \), the spherical subalgebra, (2.5)

\( J^1 = \mathbb{C}[\mathbb{C}^{2^n}] A^1, \ J^1 = \mathbb{C}[\mathfrak{h} \oplus \mathfrak{h}^\ast] A^1 \), (4.3), (4.9) \( U_c^\ast = e_c H_c e_c \), the anti-spherical subalgebra, (2.5)

\( L_c(\mu) \), simple factor of \( \Delta_c(\mu) \), (2.7) \( W = \mathfrak{S}_n \), the symmetric group, (2.1)

\( L_1 = \mathcal{O}_{\text{Hilb}^n \mathbb{C}^2}(1), \ L = \mathcal{O}_{\text{Hilb}(n)}(1) \), (4.5),(4.10) \( X_n, X_n \), isospectral Hilbert schemes, (4.3), (4.10)

\( \mathcal{O}_c \), category \( \mathcal{O} \) for \( H_c \), (2.7)

**References**

[BK] E. Backelin and K. Kreminzner, Quantum flag varieties, equivariant quantum \( \mathcal{D} \)-modules, and localization of quantum groups, math.QA/0401108.

[BGS] A. A. Beilinson, V. A. Ginzburg and V. V. Schechtman, Koszul duality, J. Geom. Phys., 5 (1988), 317-350.

[BEG1] Y. Berest, P. Etingof and V. Ginzburg, Cherednik algebras and differential operators on quasi-invariants, Duke Math. J., 118 (2003), 279-337.

[BEG2] _____, Finite dimensional representations of rational Cherednik algebras, Int. Math. Res. Not., 2003, No. 19, 1053-1088.

[BEG3] _____, Morita equivalence of Cherednik algebras, J. Reine Angew. Math., 568 (2004), 81-98.

[BG] J. N. Bernstein and S. I. Gelfand, Tensor products of finite and infinite dimensional representations of semisimple Lie algebras, Compositio Math., 41 (1981), 245-285.

[BFG] R. Bezrukavnikov, M. Finkelberg and V. Ginzburg, Rational Cherednik algebras and Hilbert schemes in characteristic \( p \), math.RT/0312474.
[BP] A. I. Bondal and A. E. Polishchuk, Homological properties of associative algebras: the method of helices, Soviet Math. Dokl., 42 (1994), 219-260.

[BKR] T. Bridgeland, A. King and M. Reid, The McKay correspondence as an equivalence of derived categories, J. Amer. Math. Soc., 14 (2001), 535-554.

[Br] K. A. Brown, Symplectic reflection algebras, Irish Math. Soc. Bull., 50 (2002), 27-49.

[BM] M. Broué and J. Michel, Sur certaines éléments réguliers des groupes de Weyl et les variétés de Deligne-Lusztig associées, in Finite Reductive Groups, Prog. Math., 141, Birkhäuser, Boston, 1997.

[CE] T. Chmutova and P. Etingof, On some representations of the rational Cherednik algebra, Rep. Theory, 7 (2003), 641-650.

[De] C. Dezhelée, Représentations de dimension finie de l’algèbre de Cherednik rationnelle, math.RT/0111210.

[DJ1] R. Dipper and G. James, Blocks and idempotents of Hecke algebras of general linear groups, Proc. London Math. Soc., 54 (1987), 57-82.

[DJ2] _____, q-tensor space and q-Weyl modules, Trans. Amer. Math. Soc., 327 (1991), 251-282.

[Ei] S. Eilenberg, Homological dimension and syzygies, Ann. Math., 61 (1956), 328-336.

[EG] P. Etingof and V. Ginzburg, Symplectic reflection algebras, Calogero-Moser space, and deformed Harish-Chandra homomorphism, Invent. Math., 147 (2002), 243-348.

[Gi] V. Ginzburg, On primitive ideals, Selecta Math., 9 (2003), 379-407.

[GGOR] V. Ginzburg, N. Guay, E. Opdam and R. Rouquier, On the category O for rational Cherednik algebras, Invent. Math., 154 (2003), 617-651.

[GK] V. Ginzburg and D. Kaledin, Poisson deformations of symplectic quotient singularities, math.AG/0212279.

[Go1] I. Gordon, Baby Verma modules for rational Cherednik algebras, Bull. London Math. Soc., 35 (2003), 321-336.

[Go2] _____, On the quotient by diagonal invariants, Invent. Math., 153 (2003), 503-518.

[GS] I. Gordon and J. T. Stafford, Rational Cherednik algebras and Hilbert schemes II: representations and sheaves, in preparation.

[Gu] N. Guay, Projective modules in the category O for the Cherednik algebra, J. Pure and Appl. Algebra, 182 (2003), 209-221.

[Ha1] M. Haiman, t, q-Catalan numbers and the Hilbert scheme, Discrete Math., 198 (1998), 201-224.

[Ha2] _____, Notes on Macdonald polynomials and the geometry of Hilbert schemes, in Symmetric Functions 2001: Surveys of Developments and Perspectives, Proceedings of the NATO Advanced Study Institute held in Cambridge, June 25-July 6, 2001, Sergey Fomin, ed. Kluwer, Dordrecht (2002).

[Ha3] _____, Hilbert schemes, polygraphs and the Macdonald positivity conjecture, Jour. Amer. Math. Soc., 14 (2001), 941-1006.

[Ha4] _____, Vanishing theorems and character formulas for the Hilbert scheme of points in the plane, Invent. Math., 149 (2002), 371-407.

[HR] R. Hartshorne, Algebraic Geometry, Graduate Texts in Mathematics 52, Springer, Heidelberg, 1977.

[JS] A. Joseph and J. T. Stafford, Modules of ℱ-finite vectors over semisimple Lie algebras, Proc. London Math. Soc., 49 (1984), 361-384.

[Ka] I. Kaplansky, Projective modules, Ann. Math., 68 (1958), 372-377.

[Le] T. Levasseur, Some properties of noncommutative regular graded rings, Glasgow Math. J., 34 (1992), 277-300.
[Lu] G. Lusztig, *Characters of reductive groups over a finite field*, Ann. Math. Studies, **107**, Princeton Univ. Press, Princeton, NJ (1984).

[Mac] I. G. Macdonald, *Symmetric Functions and Hall Polynomials, Second Ed.*, Oxford Mathematical Monographs, OUP, Oxford, 1995.

[Mt] H. Matsumura, *Commutative Algebra, Second Ed.*, Math. Lect. Note Series, Benjamin, Reading, Ma., 1980.

[Na] H. Nakajima, *Lectures on Hilbert Schemes of Points on Surfaces*, Univ. Lect. Series Vol. **18**, AMS, Providence, RI, 1999.

[Op] E. M. Opdam, A remark on the irreducible characters and fake degrees of finite real reflection groups, *Invent. Math.*, **120** (1995), 447–454.

[Sh] J.-Y. Shi, The partial order on two-sided cells of certain affine Weyl groups, *J. Algebra*, **179** (1996), 607-621.

[St] J. T. Stafford, Homological properties of the enveloping algebra $U(Sl_2)$, *Math. Proc. Cambridge Philos. Soc.*, **91** (1982), 29–37.

[SV] J. T. Stafford and M. Van den Bergh, Noncommutative curves and noncommutative surfaces, Bull. Amer. Math. Soc., **38** (2001), 171-216.

[Ta] T. Tanisaki, The Beilinson-Bernstein correspondence for quantized enveloping algebras, math.QA/0309349.

[Wa] W. Wang, Algebraic structures behind Hilbert schemes and wreath products. *Recent developments in infinite-dimensional Lie algebras and conformal field theory* (Charlottesville, VA, 2000), 271–295, Contemp. Math., **297**, Amer. Math. Soc., Providence, RI, 2002

DEPARTMENT OF MATHEMATICS, GLASGOW UNIVERSITY, GLASGOW G12 8QW, SCOTLAND

*E-mail address:* ig@maths.gla.ac.uk

DEPARTMENT OF MATHEMATICS, UNIVERSITY OF MICHIGAN, ANN ARBOR, MI 48109-1109, USA.

*E-mail address:* jts@umich.edu