Some type of commutative artin algebras*

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Introduction

The class of quasi-Frobenius (QF) algebras, i.e., selfinjective artin algebras, is one of the most interesting classes of non-semisimple artin algebras. For example, any artin algebra $A$ is a factor algebra of the trivial extension of $A$ by its dual, which is a QF algebra. Our aim is to consider the possibility of QF test of factor algebras of a polynomial ring over a field by using computers and to determine the isomorphism classes of commutative QF algebras $\Lambda$ over a field $k$ satisfying the condition

$$\Lambda/J \cong k^{(m)} \quad \text{and} \quad J^3 = 0$$

where $J$ is the radical of $\Lambda$ and $k^{(m)}$ is a product of $m$ copies of $k$ for a positive integer $m$.

In §1 we show the existence of an algorithm for deciding whether a given factor algebra of a polynomial ring is QF, and demonstrate some examples by our implementation. In §2 we consider some type of commutative QF algebras satisfying the condition above, which will be said to be of type $(1, 2, 1)$, and determine their isomorphism classes.

Throughout this paper, $k$ is a field with $k^* = k\setminus\{0\}$ and $chk$ the characteristic, all $k$-algebras mean finite dimensional commutative algebras over $k$ and isomorphisms between $k$-algebras mean $k$-algebra isomorphisms. For a $k$-algebra $\Lambda$, we denote by $\text{Rad}(\Lambda)$ and $\text{Soc}(\Lambda)$ the radical and the socle of $\Lambda$, respectively.

*More general results of the last section in this paper will appear elsewhere.
1 QF test of polynomial algebras by computer

The following result is most essential for investigating local QF algebras.

Lemma 1.1 ([1]) Let \( \Lambda \) be a local \( k \)-algebra. Then the following conditions are equivalent:

1. \( \Lambda \) is QF;
2. \( \dim_k \Lambda/\text{Rad}(\Lambda) = \dim_k \text{Soc}(\Lambda) \).

Using the lemma above and some results related to Gröbner basis theory, we have the following.

Theorem 1.2 There exists an algorithm for deciding whether, for a given ideal \( I \) of the polynomial ring \( R = k[x_1, \ldots, x_n] \) over a field \( k \), \( R/I \) is QF.

In fact, under some conditions on the base field \( k \), the algorithm can be implemented in several computer algebra systems. The following are some examples computed by our program worked on SINGULAR [4], a computer algebra system.

Example 1.3 Let \( R = \mathbb{Q}[x, y, z] \). By our program, we can easily check that the algebra \( R/(x^3, yz - z^2, y^2, xz - z^2, xy, x^2 - z^2) \) is a local QF algebra, while the algebra \( R/(x^3, yz - z^2, y^2, xz - z^2, xy, x^2) \) is local but not QF.

Example 1.4 (Tachikawa [6]) Let \( R \) be the polynomial ring \( k[x_0, x_1, \ldots, x_n] \) in \( n+1 \) variables \( x_0, x_1, \ldots, x_n \) over a field \( k \). For a positive integer \( t \), set

\[
I_t = \langle x_{[i]}x_{[i+1]} \cdots x_{[i+n-1]} - x_{[i+n]}^t | i = 0, 1, \ldots, n \rangle
\]

where \([h]\) is the residue of \( h \) modulo \( n+1 \). Then, Tachikawa proved that if \( t \neq n \), then the \( k \)-algebra \( R/I_t \) is isomorphic to a direct sum of a group algebra and a local QF algebra (and hence, it is QF). Now, we shall particularly consider the algebra in case that \( n = t - 1 \) and denote it by \( T_t \). The following is an execution result for the \( \mathbb{Q} \)-algebra \( T_3 = \mathbb{Q}[x_0, x_1, x_2]/\langle x_0x_1 - x_2^3, x_1x_2 - x_0^3, x_2x_0 - x_1^3 \rangle \) by our program, where the first three lines are our input and the rest are output.

```plaintext
> ring r=0, (x,y,z), lp;
> ideal I = (xy-z3, yz-x3, zx-y3);
> propideal(I);
<z9-z5,yz6-yz2,y2z5-y2z,y4-z4,zx-y3,xy-z3,x3-xyz
k-dimension = 27
number of components = 11
```
1

Local QF? True
Groebner Basis of I = {z+1,y+1,x-1}
  -- of (I:rad(I)) = {1}
  -- of rad(I) = {z+1,y+1,x-1}
k-basis of R/I = {1}, 1
  -- of R/(I:rad(I)) = {0}, 0
k-dim. of Loewy factors:
  upper(>): 1 (1)

2

Local QF? True
Groebner Basis of I = {z-1,y-1,x-1}
  -- of (I:rad(I)) = {1}
  -- of rad(I) = {z-1,y-1,x-1}
k-basis of R/I = {1}, 1
  -- of R/(I:rad(I)) = {0}, 0
k-dim. of Loewy factors:
  upper(>): 1 (1)

3

Local QF? True
Groebner Basis of I = {z+1,y+1,x-z}
  -- of (I:rad(I)) = {1}
  -- of rad(I) = {z+1,y+1,x-z}
k-basis of R/I = {z,1}, 2
  -- of R/(I:rad(I)) = {0}, 0
k-dim. of Loewy factors:
  upper(>): 2 (1)

4

Local QF? True
Groebner Basis of I = {z5,yz2,y2z,y4-z4,xz-y3,xy-z3,x3-xyz}
  -- of (I:rad(I)) = {z4,yz2,y2z,y4-z4,xz-y3,xy-z3,x3-xyz}
  -- of rad(I) = {z,y,x}
k-basis of R/I = {z4,3,2,z2,y2,z,y3,2,y+2,x1,1}, 11
  -- of R/(I:rad(I)) = {z3,2,z2,y2,z,y2,x2,x,1}, 10
k-dim. of Loewy factors:
  upper(>): 1 3 3 3 1 (5)

5

Local QF? True
Groebner Basis of I = {z-1,y-1,x+1}
  -- of (I:rad(I)) = {1}
  -- of rad(I) = {z-1,y-1,x+1}
k-basis of R/I = {1}, 1
  -- of R/(I:rad(I)) = {0}, 0
k-dim. of Loewy factors:
  upper(>): 1 (1)

6

Local QF? True
Groebner Basis of I = {z+1,y2+1,x-y}
  -- of (I:rad(I)) = {1}
  -- of rad(I) = {z+1,y2+1,x-y}
k-basis of R/I = {y,1}, 2
  -- of R/(I:rad(I)) = {0}, 0
k-dim. of Loewy factors:
  upper(>): 2 (1)

7

Local QF? True
Groebner Basis of I = {z-1,y2+1,x+y}
  -- of (I:rad(I)) = {1}
  -- of rad(I) = {z-1,y2+1,x+y}
k-basis of R/I = {y,1}, 2
  -- of R/(I:rad(I)) = {0}, 0
k-dim. of Loewy factors:
  upper(>): 2 (1)

8

Local QF? True
Groebner Basis of I = {z2+1,y-z,x+1}
  -- of (I:rad(I)) = {1}
  -- of rad(I) = {z2+1,y-z,x+1}
k-basis of R/I = {z,1}, 2
  -- of R/(I:rad(I)) = {0}, 0
k-dim. of Loewy factors:
  upper(>): 2 (1)

9

Local QF? True
Groebner Basis of I = {z2+1,y-1,x+z}
  -- of (I:rad(I)) = {1}
  -- of rad(I) = {z2+1,y-1,x+z}
k-basis of R/I = {z,1}, 2
  -- of R/(I:rad(I)) = {0}, 0
k-dim. of Loewy factors:
  upper(>): 2 (1)

10

Local QF? True
Groebner Basis of I = {z2+1,y-z,x+1}
  -- of (I:rad(I)) = {1}
  -- of rad(I) = {z2+1,y-z,x+1}
k-basis of R/I = {z,1}, 2
  -- of R/(I:rad(I)) = {0}, 0
k-dim. of Loewy factors:
  upper(>): 2 (1)
This output, which is arranged for want of space, shows not only $T_3$ to be a (non-local) QF algebra but also further information about this algebra. For example, \( \dim_{\mathbb{Q}}T_3 = 27 \), and the number of local components of $T_3$ is 11; four components have dimension 1, six components have dimension 2 and one ‘exceptional’ component has dimension 11 and Loewy length 5.

We also run our program in case of the algebras $T_4$ and $T_5$ over $k = \mathbb{Q}$. It is then remarkable that $T_4$ and $T_5$ as well as $T_3$ have one exceptional local component, say $C_4$ and $C_5$, of dimension 131 and 1829, respectively. Omitting to show the output, we here give only a table showing the dimension and the number of components of the algebras and the series of dimensions of the factors in Loewy series of the components $C_4$ and $C_5$.

<table>
<thead>
<tr>
<th></th>
<th>$T_4$</th>
<th>$T_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>dimension</td>
<td>( \dim T_4 = 256 )</td>
<td>( \dim T_5 = 3125 )</td>
</tr>
<tr>
<td>the number of components</td>
<td>33</td>
<td>657</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>( C_4 )</th>
<th>( C_5 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>series of dimensions of the factors in Loewy series of</td>
<td>14101622252216</td>
<td>151535</td>
</tr>
<tr>
<td>$C_4$</td>
<td>14101622252216</td>
<td>151535</td>
</tr>
<tr>
<td>$C_5$</td>
<td>151535</td>
<td>151535</td>
</tr>
</tbody>
</table>

Table 1: the dimension and the number of components of $T_4$ and $T_5$
2 Classification of QF algebras of type $(1, 2, 1)$

For the sake of completeness, we give a brief proof of the following known result.

**Lemma 2.1** For a commutative ring $\Lambda$, the following conditions are equivalent:

1. $\Lambda$ is a $k$-algebra with $\dim_k \Lambda/\text{Rad}(\Lambda) = 1$;
2. $\Lambda \cong R/I$ where $I$ is an ideal of the polynomial ring $R = k[x_1, \ldots, x_n]$ such that $(x_1, \ldots, x_n)^m \subset I \subset (x_1, \ldots, x_n)$ for some integers $m, n \geq 1$.

In particular, if $\Lambda$ is not a field, then the ideal $I$ of (2) can be chosen to satisfy $I \subset (x_1, \ldots, x_n)^2$.

**Proof.** (1) $\Rightarrow$ (2). Assume that $\Lambda$ is a $k$-algebra with $J = \text{Rad}(\Lambda)$ such that $\dim_k \Lambda/J = 1$ and $J^m = 0$ for some integer $m \geq 1$. Since $\dim_k \Lambda/J = 1$, it follows that $\Lambda = k + J$. Let $\{u_i + J \mid i = 1, \ldots, n\}$ be a $k$-basis of $J/J^2$. Then it is shown that

$$\Lambda = k + \sum_{1 \leq i_1 \leq n} ku_{i_1} + \sum_{1 \leq i_1 \leq i_2 \leq n} ku_{i_1} u_{i_2} + \cdots + \sum_{1 \leq i_1 \leq \cdots \leq i_{m-1} \leq n} ku_{i_1} \cdots u_{i_{m-1}},$$

which implies the following epimorphism:

$$\varphi: R = k[x_1, \ldots, x_n] \rightarrow \Lambda, \ f(x_1, \ldots, x_n) \mapsto f(u_1, \ldots, u_n).$$

Now, setting $I = \text{Ker} \varphi$, we will obtain the result.

(2) $\Rightarrow$ (1). This is easily shown. ■

Let $\Lambda$ be a $k$-algebra with $J = \text{Rad}(\Lambda)$ and $n$ a positive integer. Then we say that $\Lambda$ is of type $(1, n, 1)$ if

$$\dim_k \Lambda/J = 1, \ \dim_k J/J^2 = n, \ \dim_k J^2 = 1 \ \text{and} \ \dim_k J^3 = 0.$$

To determine the isomorphism classes of QF $k$-algebras $\Lambda$ with $J = \text{Rad}(\Lambda)$ satisfying the condition

$$\Lambda/J \cong k^{(m)} \ \text{and} \ J^3 = 0$$

for some $m \geq 1$, we need to consider the $k$-algebras of type $(1, n, 1)$, for the local components of QF $k$-algebras satisfying this condition are the field $k$, the serial $k$-algebra of length 2, or the $k$-algebras of type $(1, n, 1)$.

The following lemma gives the "canonical forms" of $k$-algebras of type $(1, n, 1)$.
Lemma 2.2 Let $\Lambda$ be a $k$-algebra. Then the following conditions are equivalent:

(1) $\Lambda$ is of type $(1, n, 1)$;

(2) There exist

(i) $p, q$ with $1 \leq p \leq q \leq n$, and

(ii) $a_{ij} \in k$ for $1 \leq i \leq j \leq n$ with $(i, j) \neq (p, q)$

such that

\[
\Lambda \cong k[x_{1}, \ldots, x_{n}]/\langle x_{i}x_{j} - a_{ij}x_{p}x_{q}, x_{p}^{2}x_{q} | 1 \leq i \leq j \leq n \text{ with } (i, j) \neq (p, q) \rangle.
\]

Proof. Set $R = k[x_{1}, \ldots, x_{n}]$ and $J = \langle x_{1}, \ldots, x_{n} \rangle$. For $p, q$ and $a_{ij}$'s as in (i) and (ii) of (2), set

\[
I = \langle x_{i}x_{j} - a_{ij}x_{p}x_{q}, x_{p}^{2}x_{q} | 1 \leq i \leq j \leq n \text{ with } (i, j) \neq (p, q) \rangle \subset R. \quad (#)
\]

(2) $\Rightarrow$ (1). Assume that $\Lambda = R/I$. For $f \in R$, set $\overline{f} = f + I \in \Lambda$. Since it is easy to see that $J^{3} \subset I$, it follows from Lemma 2.1 that $\Lambda$ is a $k$-algebra with $\text{Rad}(\Lambda) = J/I$. Furthermore, it can be easily seen that

\[
\{x_{1} + \text{Rad}(\Lambda)^{2}, \ldots, x_{n} + \text{Rad}(\Lambda)^{2}\} \quad \text{and} \quad \{x_{p}x_{q}\}
\]

are $k$-bases of $\text{Rad}(\Lambda)/\text{Rad}(\Lambda)^{2}$ and $\text{Rad}(\Lambda)^{2}$, respectively. Therefore, $\Lambda$ is a $k$-algebra of type $(1, n, 1)$.

(1) $\Rightarrow$ (2). Let $\Lambda$ be a $k$-algebra of type $(1, n, 1)$. By Lemma 2.1, we may assume that $\Lambda = R/H$ where $H$ is an ideal of $R$ such that $J^{3} \subset H \subset J^{2}$ and $\dim_{k} J^{2}/H = 1$. Then we can choose an $x_{p}x_{q} \notin H$ where $1 \leq p \leq q \leq n$. Since $\dim_{k} J^{2}/H = 1$, it follows that for $1 \leq i \leq j \leq n$ with $(i, j) \neq (p, q)$, there exist $a_{ij} \in k$ such that $x_{i}x_{j} - a_{ij}x_{p}x_{q} \in H$. For the $(p, q)$ and the $a_{ij}$'s, define an ideal $I$ of $R$ as in (#). Since $I \subset H$ and $\dim_{k} R/I = \dim_{k} R/H = n + 2$, we have $H = I$, which shows (2). ■

It is easy to see that in case $n = 1$, any $k$-algebra of type $(1, 1, 1)$ is isomorphic to $k[x]/\langle x^{3} \rangle$, a serial $k$-algebra of length 3. In the rest of this paper, we shall consider a non-trivial case $n = 2$, i.e., $k$-algebras of type $(1, 2, 1)$. To this, we define $k$-algebras $\Gamma$ and $\Sigma_{ab}$ $(a, b \in k)$ by

\[
\Gamma = k[x, y]/\langle x^{2}, y^{2} \rangle \quad \text{and} \quad \Sigma_{ab} = k[x, y]/\langle xy - ay^{2}, x^{2} - by^{2}, y^{3} \rangle.
\]

Then we have the following.
Lemma 2.3  (1) Any $k$-algebra $\Lambda$ of type $(1, 2, 1)$ is isomorphic to $\Gamma$ or $\Sigma_{ab}$ for some $a, b \in k$.

(2) Any QF $k$-algebra of type $(1, 2, 1)$ is isomorphic to $\Gamma$ or $\Sigma_{ab}$ for some $a, b \in k$ with $a^2 - b \neq 0$.

Proof. (1) It suffices to consider the factor algebras of $k[x, y]$ (where $x = x_1$ and $y = x_2$) in (2) of Lemma 2.2 for $(p, q) \in \{(1, 2), (2, 2)\}$. Then it can be checked that $\Lambda \cong \Gamma$ if $(p, q) = (1, 2)$ and $a_{11} = a_{22} = 0$; $\Lambda \cong \Sigma_{ab}$ for some $a, b \in k$ otherwise.

(2) Since it is easily seen that $\Gamma$ is QF, it suffices to show that $\Sigma_{ab}$ is not QF if and only if $a^2 - b = 0$. Set $J = \text{Rad}(\Sigma_{ab})$ and $S = \text{Soc}(\Sigma_{ab})$. Then we see that \{\overline{x} + J^2, \overline{y} + J^2\} and \{\overline{y}^2\} are $k$-bases of $J/J^2$ and $J^2$, respectively, and that

$$J^2 = k\overline{y}^2 \subset S = \{f \in \Sigma_{ab} \mid f\overline{x} = f\overline{y} = 0\} \subset J.$$ 

It follows from Lemma 1.1 that $\Sigma_{ab}$ is not QF if and only if $J^2 \subsetneq S$, which means that there exists $0 \neq (s, t) \in k^2$ such that $s\overline{x} + t\overline{y} \in S$. By the note above on $S$, we see that this is also equivalent to the condition $a^2 - b = 0$. □

Lemma 2.4 Let $a, b, c, d \in k$ with $a^2 - b \neq 0$ and $c^2 - d \neq 0$. Then the following conditions are equivalent:

(1) $\Sigma_{ab} \cong \Sigma_{cd}$;

(2) $\sqrt{(c^2 - d)(a^2 - b)^{-1}} \in k$.

Proof. (1) $\Rightarrow$ (2). Let $\varphi$ be a $k$-isomorphism from $\Sigma_{ab}$ to $\Sigma_{cd}$ and

$\varphi(\overline{x}) = s\overline{x} + t\overline{y} + u\overline{y}^2$ \hspace{1cm} (s, t, u \in k)

$\varphi(\overline{y}) = p\overline{x} + q\overline{y} + r\overline{y}^2$ \hspace{1cm} (p, q, r \in k).

Then,

$$0 \neq \varphi(\overline{y}^2) = \varphi(\overline{y})^2 = p^2\overline{x}^2 + 2pq\overline{x}\overline{y} + q^2\overline{y}^2 = (dp^2 + 2cpq + q^2)\overline{y}^2.$$

Set $w = dp^2 + 2cpq + q^2$. Since $\varphi$ is an isomorphism, the determinant of the matrix of $\varphi$ relative to $k$-bases \{\overline{1}, \overline{x}, \overline{y}, \overline{y}^2\} of both $\Sigma_{ab}$ and $\Sigma_{cd}$ is

$$\det \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & s & t & u \\ 0 & p & q & r \\ 0 & 0 & 0 & w \end{pmatrix} = w(qs - pt) \neq 0.$$

\[ 0 = \varphi(\overline{xy} - a\overline{y}^2) = \varphi(\overline{x})\varphi(\overline{y}) - a\varphi(\overline{y})^2 \]

Similarly,
\[ 0 = \varphi(\overline{x}^2 - b\overline{y}^2) = (ds^2 + 2cst + t^2 - bw)\overline{y}^2. \]

It follows that
\[ a = \{dsp + c(sq + tp) + tq - aw\}w^{-1} \]
\[ b = (ds^2 + 2cst + t^2)w^{-1}. \]

Now we substitute the \(a\) and \(b\) above for \((c^2 - d)(a^2 - b)^{-1}\) to obtain
\[(c^2 - d)(a^2 - b)^{-1} = w^2(qs - pt)^{-2},\]

which implies (2).

(2) \(\Rightarrow\) (1). Assume that \(u := \sqrt{(c^2 - d)(a^2 - b)^{-1}} \in k\). Then the following correspondence gives a \(k\)-isomorphism from \(\Sigma_{ab}\) to \(\Sigma_{cd}\):
\[ \overline{1} \mapsto \overline{1}, \quad \overline{x} \mapsto \overline{x} + (au - c)\overline{y}, \quad \overline{y} \mapsto u\overline{y}, \quad \overline{y}^2 \mapsto u^2\overline{y}^2, \]

which completes the proof. 

Now, consider the following algebra:
\[ \Lambda_a := k[x, y]/\langle x^2 - ay^2, xy \rangle \quad (a \in k). \]

Then we can show the following.

**Theorem 2.5** Any QF \(k\)-algebra of type \((1, 2, 1)\) is isomorphic to
\[ \Gamma \quad or \quad \Lambda_a \]

for some \(a \in k^*\). Moreover,

1. For \(a, b \in k^*, \sqrt{ab^{-1}} \in k \iff \Lambda_a \cong \Lambda_b.\)
2. (i) \(\text{ch } k \neq 2 \iff (\text{ii}) \Gamma \cong \Lambda_{-1} \iff (\text{iii}) \Gamma \cong \Lambda_c \text{ for some } c \in k^*.\)

**Proof.** Note from Lemma 2.4 that for \(a, b \in k\) with \(a^2 - b \neq 0\), \(\Sigma_{ab} \cong \Sigma_{0, b-a^2} = \Lambda_{b-a^2}\). Then the first assertion follows from Lemma 2.3.

1. This follows immediately from \(\Lambda_a = \Sigma_{0a}\) and Lemma 2.4.
(2) (i) ⇒ (ii). If $\text{ch } k \neq 2$, then the following correspondence gives a $k$-isomorphism from $\Gamma$ to $\Lambda_{-1}$:

$$
\begin{array}{c}
\overline{1} \mapsto \overline{1}, \quad \overline{x} \mapsto \overline{x} + \overline{y}, \quad \overline{y} \mapsto \overline{x} - \overline{y}, \quad \overline{xy} \mapsto -2\overline{y}^2.
\end{array}
$$

(ii) ⇒ (iii). Obvious.

(iii) ⇒ (i). Let $\varphi : \Gamma \to \Lambda_c (c \in k^*)$ be a $k$-isomorphism and

$$
\varphi(x) = s\overline{x} + t\overline{y} + u\overline{y}^2 (s, t, u \in k)
$$

$$
\varphi(y) = p\overline{x} + q\overline{y} + r\overline{y}^2 (p, q, r \in k).
$$

Then,

$$
0 = \varphi(x^2) = \varphi(x)^2 = s^2\overline{x}^2 + t^2\overline{y}^2 = (cs^2 + t^2)\overline{y}^2,
$$

from which $cs^2 + t^2 = 0$, i.e., $t^2 = -cs^2$. Similarly, $q^2 = -cp^2$. On the other hand,

$$
0 \neq \varphi(xy) = \varphi(x)\varphi(y) = (csp + tq)\overline{y}^2.
$$

Hence, $csp + tq \neq 0$. Therefore we have

$$
0 \neq (csp + tq)^2 = c^2s^2p^2 + 2cstpq + t^2q^2 = 2(c^2s^2p^2 + cstpq),
$$

which implies that $\text{ch } k \neq 2$. 

Let $\{a_i \mid (a_i \in I)\}$ be a set of representative elements of the multiplicative group $k^*$ modulo the subgroup $(k^*)^2$ of square elements, i.e., $k^*/(k^*)^2 = \{a_i(k^*)^2 \mid i \in I\}$. Then, Theorem 2.5 gives the isomorphism classes of QF $k$-algebras of type $(1, 2, 1)$ as follows.

**Corollary 2.6** (1) If $\text{ch } k \neq 2$, then the isomorphism classes of QF $k$-algebras of type $(1, 2, 1)$ are $\Lambda_{a_i} (i \in I)$. In particular, $\Gamma \cong \Lambda_{-1}$.

(2) If $\text{ch } k = 2$, then the isomorphism classes of QF $k$-algebras of type $(1, 2, 1)$ are $\Gamma$ and $\Lambda_{a_i} (i \in I)$. In particular, $\Gamma \not\cong \Lambda_{a}$ for all $a \in k^*$.

**Remark 2.7** (1) For a given field $k$, the number $N$ of the isomorphism classes of QF $k$-algebras of type $(1, 2, 1)$ is given as follows.

$$
N = \begin{cases} 
2^e & (e \geq 0) \quad \text{or} \quad \infty & (\text{ch } k \neq 2) \\
2 & \text{or} \quad \infty & (\text{ch } k = 2). 
\end{cases}
$$

(2) For any $e \geq 0$, there exists a field $k$ such that $N = 2^e$ (cf. [5, Chapter 4, §7]).

The following table shows the isomorphism classes of QF algebras of type $(1, 2, 1)$ over some typical fields $k$. 

32
Table 2: the isomorphism classes of QF $k$-algebras of type $(1, 2, 1)$

<table>
<thead>
<tr>
<th>$k$</th>
<th>$k$-isomorphism classes</th>
</tr>
</thead>
<tbody>
<tr>
<td>algebraically</td>
<td></td>
</tr>
<tr>
<td>closed fields</td>
<td>$ch, k = 2 \quad \Gamma, \Lambda_1$</td>
</tr>
<tr>
<td>finite fields</td>
<td>$ch, k \neq 2 \quad \Gamma$</td>
</tr>
<tr>
<td>finite fields</td>
<td>$ch, k = 2 \quad \Gamma, \Lambda_1$</td>
</tr>
<tr>
<td></td>
<td>$ch, k \neq 2 \quad \Lambda_a, \Lambda_\alpha (a$ is a primitive element of $k)$</td>
</tr>
<tr>
<td>$\mathbb{R}$</td>
<td>$\Gamma, \Lambda_1$</td>
</tr>
<tr>
<td>$\mathbb{Q}$</td>
<td>$\Lambda_{a_i}$</td>
</tr>
<tr>
<td></td>
<td>$({a_i \mid a_i \in \mathbb{N}}$ is the set of square free integers)</td>
</tr>
<tr>
<td>$k_0(x_1, \ldots, x_m)$</td>
<td>$\Lambda_{a_i} (i \in I,</td>
</tr>
<tr>
<td>$k_0$ is an arbitrary field</td>
<td></td>
</tr>
<tr>
<td>$p$-adic fields</td>
<td></td>
</tr>
<tr>
<td>$p = 2$</td>
<td>$\Lambda_{a_i} (\mathbb{Q}_2/(\mathbb{Q}_2)^2 = {a_i(\mathbb{Q}_2)^2 \mid i = 1, \ldots, 8})$</td>
</tr>
<tr>
<td>$Q_p$</td>
<td>$\Lambda_{a_i} (\mathbb{Q}_p/(\mathbb{Q}_p)^2 = {a_i(\mathbb{Q}_p)^2 \mid i = 1, \ldots, 4})$</td>
</tr>
</tbody>
</table>

References


