Semiprime and weakly compressible modules

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Abstract

An $R$-module $M$ is called semiprime (resp. weakly compressible) if it is cogenerated by each of its essential submodules (resp. $\text{Hom}_R(M,N)N$ is nonzero for every $0 \neq N \leq M_R$). We carry out a study of weakly compressible (semiprime) modules and show that there exist semiprime modules which are not weakly compressible. Weakly compressible modules with enough critical submodules are characterized in different ways. For certain rings $R$, including prime hereditary Noetherian rings, it is proved that $M_R$ is weakly compressible (resp. semiprime) if and only if $M \in \text{Cog}(\text{Soc}(M) \oplus R)$ and $M/\text{Soc}(M) \in \text{Cog}(R)$ (resp. $M \in \text{Cog}(\text{Soc}(M) \oplus R)$). These considerations settle two questions, namely Qu 1, and Qu 2, in [6, p 92].

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1. Introduction

Throughout this paper rings will have a nonzero identity, modules will be right and unitary. In [2], a module $M_R$ is called prime if $\text{Hom}_R(M,K)N \neq 0$ for all nonzero submodules $K, N \leq M_R$ and it is shown that $M_R$ is prime if and only if it is cogenerated by each of its nonzero submodules. A semiprime notion for modules is then obtained in [4] by setting $K = N$ in the above definition of prime modules. These semiprime modules are precisely weakly compressible modules in the sense of [1]; see for example Theorem 2.5 below. Following [6], a module $M_R$ is called weakly compressible if $\text{Hom}_R(M,N)N \neq 0$ for all nonzero $N \leq M_R$. We also call $M_R$ semiprime if every essential submodule of $M_R$ cogenerates $M_R$. In this paper, prime module means the prime module in the sense of

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2. General properties of weakly compressible modules

In this section, we investigate weakly compressible (semiprime) modules over any ring and show that semiprime modules are not necessarily weakly compressible. We give a characterization of weakly compressible modules and using this we state our main results in the next sections. Let $M$ be an $R$-module and $N$ be a submodule of $M_R$. We say that $M$ is $N$-weakly compressible if for each nonzero submodule $K$ of $N$, there exists an $R$-homomorphism $f : M \to K$ such that $f(K) \neq 0$. Thus $M_R$ is weakly compressible if and only if $M$ is $M$-weakly compressible if and only if $M$ is $N$-weakly compressible for any $0 \neq N \leq M_R$. We use the notation $N \leq_{ess} M$ to denote $N$ is an essential submodule of $M$. Also, if $X$ and $Y$ are $R$-modules, then $\cap\{\ker f \mid f : X_R \to Y_R\}$ is denoted by $\text{Rej}(X, Y)$. The module $X$ is cogenerated by $Y$ (write $X \in \text{Cog}(Y)$) if $\text{Rej}(X, Y) = 0$. In the following, some properties of weakly compressible (semiprime) modules are collected.

2.1. Lemma. (a) Let $M$ be a semiprime $R$-module. If $N$ is either an essential or fully invariant submodule of $M_R$, then $N$ is a semiprime $R$-module.

(b) The class of weakly compressible modules is closed under co-products and taking submodules.

(c) The class of semiprime modules is closed under products and co-products.

(d) Let $\Lambda$ be a non-empty set. Then $M_\Lambda$ is semiprime if and only if $M_{\Lambda}^{[\Lambda]}$ is so.

(e) Every weakly compressible module is semiprime.

(f) Let $M$ be a nonzero $R$-module and $M_1, M_2$ be submodules of $M_R$ such that there is no nonzero $R$-module $X$ which embeds in $M_1$ and $M_2$. Then $M$ is $(M_1 \oplus M_2)$-weakly compressible if and only if $M$ is $M_i$-weakly compressible for $i = 1, 2$.

(g) If $M_R$ is semiprime then $\text{ann}_R(M)$ is a semiprime ideal of $R$.

(h) $M_R$ is weakly compressible (resp. semiprime) if and only if $M_{R/I}$ is weakly compressible (resp. semiprime) where $MI = 0$ and $I \triangleright R$.

(i) If $M_R$ is weakly compressible and $N$ is a fully invariant closed submodule of $M_R$, then $M/N$ is a weakly compressible $R$-module.
Proof. (a) If \( N \leq_{\text{ess}} M_R \), then it is easy to see that \( N_R \) is semiprime. Let \( N \) be a fully invariant of \( M_R \) and \( K \leq_{\text{ess}} N \). There exists a submodule \( L \) of \( M_R \) such that \( N \cap L = 0 \) and \( N \oplus L \leq_{\text{ess}} M \). Thus \( K \oplus L \leq_{\text{ess}} M \). By our assumption \( M \in \text{Cog}(K \oplus L) \). Hence there exists an injective homomorphism \( \theta : M \to K^I \oplus L^I \) for some set \( I \). Since \( N \) is fully invariant of \( M_R \), it is easy to see \( \pi \theta(N) = 0 \), where \( \pi : K^I \oplus L^I \to L^I \) is the natural projection. It follows that \( \theta(N) \), and hence \( N \) embeds in \( K^I \), proving that \( N_R \) is semiprime.

(b) We only prove the co-product case. Let \( \{M_i\}_{i \in I} \) be a family of weakly compressible \( R \)-modules and \( N \) be any nonzero submodule of \( \oplus_{i \in I} M_i \). It is easy to verify that there exists subset \( J \) of \( I \) such that the canonical projection \( \pi : \oplus_{i \in I} M_i \to \oplus_{j \in J} M_j =: W \) is one to one on \( N \) and \( \pi(N) \cap M_j \neq 0 \) for each \( j \in J \); see also [9, Lemma 2.1]. Because \( M_j \) is weakly compressible for each \( j \in J \), there are homomorphisms \( f_j \in \text{Hom}_R(M_j, \pi(N) \cap M_j) \) such that \( f_j(\pi(N) \cap M_j) \neq 0 \). Now let \( f = \sum_{j \in J} f_j : W \to \pi(N) \) and \( \theta = \pi^{-1} f \pi \). Then \( \theta : M \to N \) such that \( \theta|_N \neq 0 \), as desired.

(c) Let \( N \) be an essential submodule of product \( \prod_{i \in I} M_i \) where each \( M_i \) is a semiprime module (the co-product case has a similar proof). Note that for each \( i \in I \) we have \( (N \cap M_i) \leq_{\text{ess}} M_i \). Thus by our assumption, \( M_i \in \text{Cog}(N) \) for each \( i \in I \). It follows that \( \prod_{i \in I} M_i \in \text{Cog}(N) \).

(d) The necessity follows by part (c). Conversely, let \( M(N) \) be semiprime and \( N \leq_{\text{ess}} M \). Then \( N(N) \leq_{\text{ess}} M(N) \). Thus \( M(N) \in \text{Cog}(N(N)) \). This shows that \( M \in \text{Cog}(N) \), as desired.

(e) This is obtained by [6, Theorem 5.1(b)].

(f) Just note that if \( N \) is a nonzero submodule of \( M_1 \oplus M_2 \), then by our assumption, either \( N \cap M_1 \neq 0 \) or \( N \cap M_2 \neq 0 \).

(g) This follows by [6, Proposition 5.5(viii)].

(h) This has a routine argument.

(i) Let \( N \) be a fully invariant closed submodule of \( M_R \). By [5, Proposition 6.32], there exists \( K \leq M_R \) such that \( N \) is a complement to \( K \) in \( M \). It follows that \( K \oplus N/N \) is an essential submodule of \( M/N \). Hence, it is enough to show that \( M/N \) is \((K \oplus N/N)\)-weakly compressible. Now let \( x + N \in (K \oplus N/N) \) for some nonzero element \( x \in K \). Since \( M_R \) is weakly compressible, there exists a homomorphism \( f : M \to xR \) such that \( f(x) \neq 0 \). We have \( f(N) = 0 \) because \( N \) is a fully invariant submodule of \( M \). Thus \( f \) induces a homomorphism \( \bar{f} : M/N \to xR \oplus N/N \) such that \( \bar{f}(x + N) \neq 0 \). The proof is complete.

An \( R \)-module \( M \) is called \textit{torsionless} if it is cogenerated by \( R \). The following result may be already in the literature, but we cannot spot it, we give a proof for the sake of the reader.

\[ \textbf{2.2. Proposition.} \quad \text{Every torsionless module over a semiprime ring is weakly compressible.} \]

\textbf{Proof.} Let \( R \) be a semiprime ring and \( M \) be an \( R \)-submodule of \( R^I \) for some set \( I \). Suppose that \( N \) is a nonzero submodule of \( M \). Thus \( \pi_I(N) \neq 0 \) for some \( i \in I \), where \( \pi_I \) is the canonical projection from \( R^I \) to \( R \). Since \( R \) is a semiprime ring, \( (\pi_I(N))^2 \neq 0 \). Hence there exists \( x \in N \) such that \( x\pi_I(N) \neq 0 \). Now let \( f = \epsilon_x \pi \) where \( \pi|_M = \pi \) and \( \epsilon_x : R \to xR \) is left multiplication by \( x \). Then \( f : M \to N \) is a homomorphism such that \( f(N) \neq 0 \), proving that \( M_R \) is weakly compressible.

\[ \textbf{2.3. Corollary.} \quad \text{Let} \ R \text{ be a ring and} \ \{I_i\}_{i \in A} \text{ be a family of semiprime ideals in} \ R. \text{ Then} \ \oplus_{i \in A}(R/I_i)^{N_i} \text{ is a weakly compressible} \ R\text{-module, where each} \ N_i \text{ is a set.} \]

\textbf{Proof.} This follows by Proposition 2.2 and Lemma 2.1(b),(h).
2.4. Lemma. Every nonsingular R-module M contains an essential submodule isomorphic to ⊕Ii, where each Ii is a right ideal of R.

Proof. Let x be any nonzero element of MR. Then annR(x) is not an essential right ideal of R by our assumption on MR. Thus there exists a nonzero right ideal I of R such that annR(x) ∩ I = 0. Note that Ix ≅ xI. Therefore every nonzero submodule of M contains a nonzero submodule that is isomorphic to a right ideal of R. Now suppose that Ω = {N ≤ MR} there is I ≤ R_R such that I ≅ N}. If {Nλ}_λ∈Λ is a maximal independent family of submodules in Ω, then by what we have already proved, ⊕_λ∈Λ Nλ is an essential submodule of M_R.

In [6, Theorem 5.1], it is shown that an R-module M is weakly compressible if and only if Hom_R(M,N)^2 ≠ 0 for all nonzero N ≤ M if and only if N ∩ Rej(M,N) = 0 for any nonzero N ≤ M_R. In the following we give more equivalent conditions for a nonzero module M to be weakly compressible. We should note that in [1], a module M_R is called “weakly compressible” if for every 0 ≠ N ≤ M_R there exists f ∈ Hom_R(M,N) with f^2 ≠ 0. Such a module M is clearly weakly compressible (in the sense of [6]), but we have been unable to find in the literature a proof to show the converse is true. A proof of this is given below for completeness. Recall that for any R-module M the set {m ∈ M | ann_R(m) ≤ ess R_R} is denoted by Z(M).

2.5. Theorem. The following conditions are equivalent for a nonzero R-module M.
(a) M_R is weakly compressible.
(b) For every nonzero N ≤ M, there exists f ∈ Hom_R(M,N) such that f^2 ≠ 0.
(c) N ≅ Rej(M,N), for every nonzero N ≤ M_R.
(d) M_1 ⊆ Rej(M,M_2) for all nonzero isomorphic R-modules M_1 and M_2.
(e) There exists an essential submodule N of M_R such that N is weakly compressible.
(f) There exists submodule N of M_R such that N is N-weakly compressible and M/N is weakly compressible.
(g) There exists a semiprime ideal I of R such that MI = 0 and M is Rej(M,R/I)-weakly compressible.
(h) M is Z(M)-weakly compressible and M/Z_2(M) ∈ Cog(R/I) for some semiprime ideal I ⊆ ann_R(M).

Proof. (a) ⇒ (b). Let N be a nonzero submodule of M_R and for every f ∈ Hom_R(M,N), f^2 = 0. It is easy to verify that fg = −gf for all f, g ∈ Hom_R(M,N) (note that (f + g)^2 = 0). By (a), there exist f ∈ Hom_R(M,N) and g ∈ Hom_R(M,f(M)) such that f(N) ≠ 0 and g(f(M)) ≠ 0. Since gf = −fg, we have fg ≠ 0. If follows that f^2(M) ≠ 0 because g(M) ⊆ f(M). This contradicts our assumption.
(b) ⇒ (c). Let N be any nonzero submodule of M_R. Suppose that there exists an injective homomorphism θ : N → Rej(M,N). Since N ≃ θ(N), Rej(M,θ(N)) = Rej(M,N). Hence, if f ∈ Hom_R(M,θ(N)) then Imf ⊆ Rej(M,θ(N)). This shows that f^2 = 0 for every f ∈ Hom_R(M,θ(N)). This contradicts (b).
(c) ⇒ (d). Just note that if M_1 ⊆ Rej(M,M_2), then M_1 is isomorphic to a submodule N of M such that N ⊆ Rej(M,N).
(d) ⇒ (a), (a) ⇔ (e) and (a) ⇒ (f) are clear.
(a) ⇒ (g). This is hold because ann_R(M) is a semiprime ideal of R by Lemma 2.1.
(g) ⇒ (f). Let N = Rej(M,R/I). Then M/N ∈ Cog(R/I). Now apply Proposition 2.2 and Lemma 2.1(h).
(f) ⇒ (a). Suppose (f) holds and K is a nonzero submodule of M_R. We shall show that there exists g ∈ Hom_R(M,K) with g(K) ≠ 0. Now if K ∩ N = 0, then we are done by our assumption on N. If K ∩ N = 0, then consider the submodule (N ⊕ K)/N of M/N. Since M/N is weakly compressible, we can deduce such g exists.
(a) ⇒ (h). First note that for any $R$-module $M$, we have $M/Z_2(M)$ is a nonsingular $R$-module. Let $I = \text{ann}_R(M)$. Thus $M/Z_2(M) \in \text{Cog}(R/I)$ by Lemmas 2.1(i) and 2.4, the proof is complete.

(h) ⇒ (f). Since $Z(M) \leq_{\text{ess}} Z_2(M)$, it is clear that $M_R$ is also $Z_2(M)$-weakly compressible. The result is now obtained by Proposition 2.2.

2.6. Corollary. (a) If $R$ is a right self injective ring, then $M_R$ is weakly compressible if and only if $Z(M)$ is $Z(M)$-weakly compressible.

(b) If $R$ is a right V-ring (i.e., simple $R$-modules are injective) and $M/Soc(M)$ is a weakly compressible $R$-module, then $M_R$ is weakly compressible.

Proof. (a) Let $R$ be a right self injective ring. For the sufficiency, let $N$ be complement to $Z(M)$ in $M_R$. By Theorem 2.5(e), we shall show that $M$ is $Z(M)\oplus N$-weakly compressible. Since $R$ is right self injective, every nonsingular cyclic $R$-module is isomorphic to a direct summand of $R_R$ and hence it is an injective $R$-module. It follows that $M$ is $N$-weakly compressible. The proof is now completed by Lemma 2.1(f). The converse is clear.

(b) By Theorem 2.5(f).

2.7. Proposition. The following statements hold for an extending module $M_R$.

(a) $M_R$ is weakly compressible if and only if $Z_2(M)$ and $M/Z_2(M)$ are weakly compressible $R$-modules.

(b) If $\text{Soc}(R_R) \leq_{\text{ess}} R_R$, then $M_R$ is semiprime if and only if $Z_2(M)$ and $M/Z_2(M)$ are semiprime $R$-modules.

Proof. Let $N = Z_2(M)$. Since $M$ is extending, it is known that $M \cong N \oplus M/N$.

(a) Apply Theorem 2.5(f) and note that $N$ is weakly compressible if and only if $M$ is $N$-weakly compressible.

(b) Since $\text{Soc}(R_R) \leq_{\text{ess}} R_R$, it is easy to verify that $Z(V^\Lambda) = (Z(V))^\Lambda$ for any $R$-module $V$ and any set $\Lambda$. Now let $M_R$ be semiprime. By Lemma 2.1(a), $N_R$ is semiprime. Suppose that $K/N \leq_{\text{ess}} M/N$. Then $K \leq_{\text{ess}} M$ and so there exists an injective homomorphism $\theta : M \to K^\Lambda$. Define $\alpha : M/N \to K^\Lambda/N^\Lambda$ by $\alpha(m + N) = \theta(m) + N^\Lambda$. Clearly $\alpha$ is a homomorphism. If $\alpha(m + N) = 0$ then $\theta(m) = \{n_\lambda\}_{\lambda \in \Lambda} \in N^\Lambda$. For each $\lambda$, we have $n_\lambda J_\lambda \subseteq Z(M)$ where $J_\lambda \leq_{\text{ess}} R_R$. Thus $\theta(mJ) \subseteq (Z(M))^\Lambda$ where $\cap \lambda J_\lambda = J$. By our assumption on $R$, $J \leq_{\text{ess}} R_R$ and $\theta(mJ) \subseteq Z(K^\Lambda)$. It follows that $mJ \subseteq Z(M)$ because $\theta$ is one to one. Hence $m \in N$, proving that $\alpha$ is injective and so $M/N$ is weakly compressible.

For every module $M_R$ the intersection of all maximal submodule of $M$ is denoted by $\text{Rad}(M)$. If $M$ does not have maximal submodules, we put $\text{Rad}(M) = M$.

2.8. Examples and Remarks. (a) There are modules $N$ such that $\text{Rad}(N) = 0$ but $N$ is not semiprime. Let $P$ be the set of all prime integer numbers and $p \in P$. Consider the $\mathbb{Z}$-module $N = \{m/p^n \mid m, n \in \mathbb{Z}, n \geq 1\}$. Then for each $q \in P \setminus \{p\}$, $qN$ is a maximal submodule of $N_N$. To see this, note that $qN \neq N$ and suppose that $K$ is any submodule of $N_N$ such that $qN \subseteq K$ and $m/p' \in K \setminus qN$. Hence $(m, q) = 1$. Also, if $a/p' \in K$ for some $r \geq 1$ and $(a, q) = 1$, then $1/p' \in K$. It follows that $1/p' \in K$ for all $n \geq 1$ (take $n \geq t$ or $n \leq t$). Therefore $K = N$ and so $qN$ is a maximal submodule. Clearly $\bigcap_{q \neq p} qN = 0$ and hence $\text{Rad}(N) = 0$. Now if $N_N$ is semiprime, then $\text{Hom}_{\mathbb{Z}}(N, \mathbb{Z}) \neq 0$ and since $N$ is uniform, we must have $N \twoheadrightarrow \mathbb{Z}$, contradiction.

(b) A direct summand of a semiprime module is not necessarily a semiprime module. Assume that $P$ and $N$ are as stated in (a). Let $W = \bigoplus_{p \in P} \mathbb{Z}_p$ and $L = W \oplus N$. We show that $L_\mathbb{Z}$ is semiprime. Since $\bigcap_{q \neq p} qN = 0$, $N \in \text{Cog}(W)$. Thus from $\text{Soc}(L) = W$, $L_\mathbb{Z}$ is a direct summand of $L$ which is semiprime, but $L_\mathbb{Z}$ is not semiprime.
we have $L \in \text{Cog}(_{\text{Soc}(L)}).$ It follows that $L$ is semiprime as a $\mathbb{Z}$-module because every essential submodule of $L$ contains $\text{Soc}(L)$.

(c) Lemma 2.1(b) and part (b) show that the $\mathbb{Z}$-module $L$ in (b) is semiprime which is not weakly compressible. Furthermore, let $R$ be a commutative regular ring which is not semi-Artinian (for example $R = \prod \mathbb{Z}_2$). Since $R$ is a regular ring, $\text{Rad}(M) = 0$ for all $R$-modules. Hence every $R$-module embeds in a semiprime $R$-module by Lemma 2.1(c). On the other hand, since $R$ is not semi-Artinian, there exists an $R$-module $M$ which is not weakly compressible by [10, Corollary 3.5]. Now if $M$ embeds in a semiprime $R$-module $L$, then $L$ is not weakly compressible by Lemma 2.1(b).

(d) The condition (h) in Theorem 2.5 shows that the study of weakly compressible modules can be reduced to the study of such modules when they are either singular or nonsingular; see Proposition 2.7. However we shall note that, in general, the condition $M$ is $Z(M)$-weakly compressible is stronger than $Z(M)$ is a weakly compressible $R$-module. For example, if $R = \left[ \begin{array}{cc} \mathbb{Z} & 0 \\ \mathbb{Z}_2 & \mathbb{Z}_2 \end{array} \right]$, then $Z(R_K) = \left[ \begin{array}{cc} 0 & 0 \\ \mathbb{Z}_2 & 0 \end{array} \right] =: I$. Thus $I_{R_K}$ is weakly compressible, but $R$ is not $I$-weakly compressible because $\text{Hom}_R(R, I)(I) = 0$.

(e) In view of the condition (c) in Theorem 2.5, we note that the condition $N \leftrightarrow \text{Rej}(M, N)$ is weaker than $N \subseteq \text{Rej}(M, N)$. For if we consider $I$ as left ideal in $R$, then $I \simeq \left[ \begin{array}{cc} 0 & 0 \\ 0 & \mathbb{Z}_2 \end{array} \right] =: J$ as left $R$-modules and $\text{Rej}(R, J) = \text{ann}_R(J) = \left[ \begin{array}{cc} \mathbb{Z} & 0 \\ \mathbb{Z}_2 & 0 \end{array} \right]$. Hence $J \nvdash \text{Rej}(R, J)$, but $J \not\subseteq \text{Rej}(R, J)$.

In the following nonsingular weakly compressible modules are characterized and some corollaries are given. For certain module $M_R$, the condition (c) of Theorem 2.5 is reduced to the ideals of $R$; see below.

2.9. Proposition. Let $M$ be a module over a semiprime ring $R$ and $Z(\text{Rej}(M, R)) = 0$. Then the following statements are equivalent.

(a) $M_R$ is weakly compressible.

(b) For all nonzero right ideal $I$ of $R$, $I \not\leftrightarrow \text{Rej}(M, I)$.

(c) $M \in \text{Cog}(R)$.

Proof. (a) $\Rightarrow$ (b). By Theorem 2.5(c).

(b) $\Rightarrow$ (c). If $\text{Rej}(M, R)$ is nonzero then by Lemma 2.4, $I \leftrightarrow \text{Rej}(M, R)$ for some nonzero right ideal $I$ of $R$. It follows that $I \nvdash \text{Rej}(M, I)$, a contradiction. Therefore $\text{Rej}(M, R) = 0$ and so (c) holds.

(c) $\Rightarrow$ (a). By Proposition 2.2. □

2.10. Corollary. Let $M$ be a nonsingular $R$-module. Then $M_R$ is weakly compressible if and only if there exists a semiprime ideal $I \subseteq \text{ann}_R(M)$ such that $M \in \text{Cog}(R/I)$.

Proof. Note that $Z(M_{R/I}) \subseteq Z(M_R)$, for any ideal $I$ of $R$. The result is now obtained by Proposition 2.9. □

A ring $R$ is called right (left) duo ring if every right(left) ideal of $R$ is two sided.

2.11. Corollary. Let $M$ be a faithful module over a right(left) duo ring $R$. Then $M_R$ is weakly compressible if and only if $M_R$ is $Z(M)$-weakly compressible, $M/Z(M) \in \text{Cog}(R)$ and $R$ is a semiprime ring.
Proof. It is easy to verify that every semiprime right (left) duo ring must be reduced and hence it is a nonsingular ring [5, Lemma 7.8]. Thus \( Z(M) = Z_2(M) \). Suppose now \( M \) is weakly compressible, then \( R \) must be a semiprime ring because \( M_R \) is faithful. Also \( M/Z(M) \) is weakly compressible by Lemma 2.1(i), and so \( M/Z(M) \in \text{Cog}(R) \) by Proposition 2.9. The converse is obtained by Theorem 2.5(h).

3. Weakly compressible modules with enough critical submodules

We are now going to investigate semiprime and weakly compressible modules over rings with Krull dimensions. Let \( M \) be an \( R \)-module. Following [7, Chapter 6], the Krull dimension of \( M_R \) will be denoted by \( \text{K.dim}(M) \). Modules with Krull dimensions are known to have finite uniform dimensions [7, Lemma 6.2.6]. Let \( \alpha \geq 0 \) be an ordinal number. A module \( M_R \) is called \( \alpha \)-critical if \( \text{K.dim}(M) = \alpha \) and \( \text{K.dim}(M/N) < \alpha \) for every nonzero submodule \( N \) of \( M_R \). A module is then called critical if it is \( \beta \)-critical for some ordinal number \( \beta \). The submodule \( \bigcap \{ K \leq M_R \mid M/K \text{ is } \alpha \text{-critical} \} \) is denoted by \( J_\alpha(M) \).

3.1. Lemma. Let \( M \) be a semiprime \( R \)-module, \( T \) be any nonzero submodule of \( M \). If there exist submodules \( W \) and \( N \) of \( M \) such that \( N \in \text{Cog}(T) \), \( T \notin \text{Cog}(W) \) and \( (N \oplus W) \leq_{ess} M \), then \( T \notin \text{Rej}(M,T) \).

Proof. Since \( M_R \) is semiprime, there exists an injective homomorphism \( f : M \to N^A \oplus W^A \) for some set \( A \). Since \( T \notin \text{Cog}(W) \), \( \pi f(T) \neq 0 \), where \( \pi : N^A \oplus W^A \to N^A \) is a natural projection. By our assumption, \( N^A \in \text{Cog}(T) \). Hence there exists a homomorphism \( \varphi : N^A \to T \) such that \( \varphi \pi f(T) \neq 0 \), proving that \( T \notin \text{Rej}(M,T) \).

The following lemma is needed. That is just obtained by the definition of critical submodules.

3.2. Lemma. Let \( U \) and \( V \) be critical \( R \)-modules and \( f : U \to V \) be a nonzero homomorphism. Then either \( \text{Ker}(f) = 0 \) or \( \text{K.dim}(V) < \text{K.dim}(U) \).

We say that a module \( M_R \) has enough critical submodules if every nonzero submodule has a nonzero submodule with Krull dimension (note, modules with Krull dimension have critical submodules).

3.3. Lemma. Suppose that \( M_R \) has enough critical submodules and \( \alpha = \text{Min}\{ K, \text{dim}(N) \mid 0 \neq N \leq M_R \} \). If \( M_R \) is semiprime, then \( N \notin \text{Rej}(M,N) \) for every submodule \( N \leq M_R \) with \( \text{K.dim}(N) = \alpha \).

Proof. Let \( N \leq M_R \) and \( \text{K.dim}(N) = \alpha \). By [7, Lemma 6.2.10], there exists a critical submodule \( T \leq N \). By choosing of \( \alpha \), \( T \) is \( \alpha \)-critical. Let \( \Lambda = \{ T' \leq M_R \mid T' \in \text{Cog}(T) \} \}, \{ T'_i \}_{i \in I} \) be a maximal independent family of elements in \( \Lambda \) and \( N' = \oplus_{i \in I} T'_i \). Since \( M_R \) has enough critical submodules, \( N' \oplus W \leq_{ess} M_R \) where \( W \) is a direct sum of critical submodules. Therefore by Lemma 3.2, \( T \notin \text{Cog}(W) \) and so \( T \notin \text{Rej}(M,T) \) by Lemma 3.1. The proof is complete.

A module \( M_R \) is called compressible if it embeds in every submodule of \( M \). By Lemma 3.2 critical weakly compressible modules are compressible.

3.4. Theorem. Suppose that \( M_R \) has enough critical submodules and \( \beta = \text{Sup}\{ K, \text{dim}(N) \mid N \text{ is a critical submodule of } M_R \} \). Then the following statements are equivalent.

(a) \( M_R \) is semiprime module and \( J_\beta(M) = 0 \).
(b) \( M_R \) embeds in a product of \( \beta \)-critical compressible submodules of \( M_R \).
(c) \( M_R \) embeds in a product of \( \beta \)-critical compressible \( R \)-modules.

Furthermore, each of the above conditions implies that \( M_R \) is weakly compressible.
Proof. (a) ⇒ (b). We first show that every critical submodule of $M_R$ is $\beta$-critical. Let $C$ be any critical submodule of $M_R$. By our assumption, $C \ni J_\beta(M)$. It follows that there exists a homomorphism $f$ from $M_R$ to a $\beta$-critical module $T_R$ such that $f(C) \neq 0$. By Lemma 3.2, $f$ is one to one on $C$. Thus $C_R$ is $\beta$-critical, as desired. Now since $M_R$ has enough critical submodules, $\beta = \min\{\text{Kdim}(N) \mid N \neq M_R\}$. Therefore $M_R$ is weakly compressible by Lemma 3.3. Hence, every critical submodule of $M_R$ is also weakly compressible as well as compressible. The proof is now complete because $M$ contains an essential submodule that is a direct sum of $\beta$-critical compressible submodules.

(b) ⇒ (c). This is clear.

(c) ⇒ (a). It is easy to see that $J_\beta(M) = 0$. As we see in the proof of (a) ⇒ (b), for every critical submodule $C$ of $M_R$ there exist a $\beta$-critical compressible $R$-module $T$ and homomorphism $\alpha : M \to T$ such that $\alpha$ is one to one on $C$. Since now $T_R$ is compressible, there exists an injective homomorphism $f : T \to C$. Thus $f_\alpha(C) \neq 0$, proving that $C \ni \text{Rej}(M, C)$. It follows that $M_R$ is weakly compressible, hence semiprime.

3.5. Remark. Let $R = \mathbb{Z}$, $M = \mathbb{Z}_2 \oplus \mathbb{Z}$ and $\beta$ be as stated in Theorem 3.4. Then $M_R$ is weakly compressible and $\beta = 1$, but $J_\beta(M) \neq 0$ because $M \notin \text{Cog}(R)$.

3.6. Lemma. Suppose that $M$ is an $R$-module, $\{V_i\}_{i \in I}$ is a family of nonzero submodules of $M_R$, $\{W_j\}_{j \in J}$ is a family of $R$-modules and the following conditions (a), (b) hold,

(a) For every nonzero submodule $N$ of $M_R$, there exists $V_i \subseteq N$ for some $i \in I$.

(b) For every $i \in I$, there exist $j \in J$ and homomorphism $f : M \to W_j$ such that $\text{Ker}f \cap V_i = 0$.

If $M_R$ has finite uniform dimension, then there exists a finite subset $A$ of $J$ such that $M_R$ embeds in $\bigoplus_{j \in A}W_j$.

Proof. Let $A = \{u.\text{dim}(\text{Ker}f) \mid f \in \text{Hom}_R(M, \bigoplus_{j \in A}W_j)\}$ and $A$ is a finite set. By hypothesis $A$ is a nonempty set. Let $n$ be the smallest element in $A$, and $f : M \to \bigoplus_{j \in A}W_j$ such that $u.\text{dim}(\text{Ker}f) = n$. Let $K = \text{Ker}f$. If $K \neq 0$, then by (a), there exists $i \in I$ such that $V_i \subseteq K$ and by (b) there exists a homomorphism $g : M \to W_t$ such that $\text{Ker}g \cap V_i = 0$ for some $t \in J$. Now, define $h : M \to \bigoplus_{j \in A}W_j \oplus W_t$ by $h(m) = (f(m), g(m))$ for all $m \in M$. It is clear that $\text{Ker}h = K \cap \text{Ker}g$. Since $\text{Ker}h \cap V_i = 0$, $\text{Ker}h$ is not essential submodule of $K$. Hence $u.\text{dim}(\text{Ker}h) < u.\text{dim}(\text{Ker}f)$. This contradicts the choice of $f$. Therefore $K = 0$ and so $M$ embeds in $\bigoplus_{j \in A}W_j$, as desired.

3.7. Theorem. The following statements are equivalent for a nonzero module $M_R$.

(a) $M_R$ is weakly compressible with finite uniform dimension and $Z(M)$ has Krull dimension.

(b) $M_R$ is weakly compressible with finite uniform dimension and $Z(M)$ has enough critical submodules.

(c) $M_R$ embeds in a finite direct sum $\bigoplus W_i$ of cyclic compressible submodules of $M_R$ such that each $W_i$ is either uniform nonsingular or critical singular.

(d) $M_R$ embeds in $W \oplus V$ such that $W_R$ and $V_R$ are weakly compressible, $W$ is nonsingular with finite uniform dimension and $V$ is singular with Krull dimension.

Proof. (a) ⇒ (b) and (c) ⇒ (d) are clear. (d) ⇒ (a) is obtained by Lemma 2.1(b) and the fact that modules with Krull dimensions have finite uniform dimensions. We shall show that (b) ⇒ (c).

Apply Lemma 3.6 for $\{V_i\}_{i \in I} = \{W_j\}_{j \in J}$ = $\{C \subseteq M_R \mid C$ is either uniform nonsingular or critical singular}. By our hypothesis, the condition (a) of Lemma 3.6 holds. Note that every endomorphism of the above submodules $C$ is either injective or zero (Lemma 3.2). Hence, by the weakly compressible condition on $M$, we have the submodules $C$
are compressible and the condition (b) of Lemma 3.6 holds. The proof is now complete because any compressible module embeds in each of its cyclic submodule.

3.8. Corollary. The following statements are equivalent for a nonzero module $M_R$.
(a) $M_R$ is weakly compressible with Krull dimension.
(b) $M_R$ is weakly compressible with finite uniform dimension and it has enough critical submodules.
(c) $M_R$ embeds in a finite direct sum of critical compressible submodules of $M_R$.
(d) $M_R$ embeds in a finite direct sum of critical compressible $R$-modules.

Proof. This follows by Theorem 3.7. □

The following result is a consequence of Theorem 3.7 which should be compared with Corollary 2.10.

3.9. Corollary. If $M_R$ is a nonsingular weakly compressible module with finite uniform dimension, then $M_R$ embeds in a finitely generated free $R$-module.

Proof. Note that every nonsingular compressible $R$-module embeds in $R$ (Lemma 2.4). Thus the result is obtained by Theorem 3.7(c). □

4. Weakly compressible modules over singular semi-Artinian rings

In [8, Main Theorem], it is shown that a $Z$-module $M$ is weakly compressible if and only if $Z(M)$ is semisimple and $M/Z(M)$ is torsionless. We conclude the paper with a characterization of weakly compressible (semiprime) modules over certain rings including prime hereditary Noetherian rings. If $R$ is a hereditary Noetherian ring, then by [7, Proposition 5.4.5], every nonzero singular $R$-module has a nonzero socle. We call such rings $R$ right singular semi-Artinian.

4.1. Theorem. Suppose that $R$ is a right singular semi-Artinian ring. $M_R$ is nonzero and $MI = 0$ for some ideal $I$ of $R$. If $M_R$ is semiprime then $M \in \text{Cog}(\text{Soc}(M) \oplus R/I)$. The converse holds if $I$ is a prime ideal of $R$.

Proof. Since $R/I$ is also a right singular semi-Artinian ring, we can suppose that $I = 0$. Let $M_R$ be semiprime and $\text{Soc}(Z(M)) \oplus K \leq_{ess} M_R$ where $K \leq M_R$. By our assumption on $R$, we have $Z(K) = 0$. Thus $M \in \text{Cog}(\text{Soc}(M) \oplus R)$ by Lemma 2.4.

Conversely, assume that $M \in \text{Cog}(\text{Soc}(M) \oplus R)$ and $R$ is a prime ring. Let $N$ be any essential submodule of $M_R$. We have $\text{Soc}(Z(N)) \oplus L \leq_{ess} N$ such that $L \cong \bigoplus_{i \in I} I_i$ where each $I_i$ is a right ideal of $R$. Since $\text{Soc}(M)$ lies in any essential submodule of $M_R$, we deduce from the hypothesis that $M \in \text{Cog}(\text{Soc}(N) \oplus L \oplus R)$. Now $\text{Rej}(R,L) = \text{ann}_R(L) = 0$ because $R$ is prime ring. It follows that $R \in \text{Cog}(L)$ and hence $M \in \text{Cog}(N)$, proving that $M_R$ is semiprime. □

4.2. Remark. Let $R$ be any ring and $M$ be a nonzero $R$-module. Then $M_R$ is a subdirect product of prime modules if and only if $M$ is cogenerated by prime modules. Now let $M_R$ be a weakly compressible $R$-module and $A = \text{ann}_R(M)$. Note that $R/A$ is subdirect product of prime $R$-modules. Therefore if $M_R$ satisfies the conditions of Theorem 3.4 or 3.7 or 4.1, then $M$ is cogenerated by prime modules and hence it is a subdirect product of prime $R$-modules. This gives a partially answer to the open problem 1 of [6].

4.3. Proposition. Let $M_R$ be semiprime and $L \leq M_R$. Then the following statements hold.
(a) If $\text{Soc}(L)$ is finitely generated then $\text{Soc}(L)$ is a direct summand of $M$. In particular, if $M$ has acc on direct summands, then $\text{Soc}(M)$ is a direct summand of $M$.
(b) If every cyclic submodules of $L$ has a finitely generated socle then $\text{Soc}(L)$ is a closed
Proof. (a) Suppose that the length of $\text{Soc}(L)$ is $n$. Let $T_1$ be a simple submodule of $L_R$, $N = \sum \{ T' \leq M_R \mid T' \cong T_1 \}$ and $W$ be a complement to $N$ in $M$. Then $T_1 \not\in \text{Cog}(W)$ and so by Lemma 3.1, $T_1 \not\subseteq \text{Rej}(M, T_1)$. Hence there exists a nonzero homomorphism $f : M \to T_1$ such that $f(T_1) \neq 0$. Clearly $\text{Ker}(f)$ is a maximal submodule of $M_R$. It follows that $M = T_1 \oplus A_1$ where $A_1 = \text{ker} f$, and hence $L = T_1 \oplus (L \cap A_1)$. If $\text{Soc}(L \cap A_1) = 0$, then $\text{Soc}(L) = T_1$ and we are done. If not, consider the simple submodule $T_2$ of $L \cap A_1$. Again we deduce that $T_2$ is a direct summand of $M$ and hence of $A_1$. Thus $M = T_1 \oplus T_2 \oplus A_2$ for some $A_2 \leq M$ and $L = T_1 \oplus T_2 \oplus (L \cap A_2)$. Continue to obtain $T_1 \oplus T_2 \oplus \ldots \oplus T_n$ is a direct summand of $M_R$, as desired. The last statement is now clear.

(b) If $\text{Soc}(L) \leq_{ess} C$ and $x \in C \subseteq L$, then $\text{Soc}(xR) \leq_{ess} xR$. Hence by our assumption and (a), we must have $xR = \text{Soc}(xR) \subseteq \text{Soc}(L)$. It follows that $\text{Soc}(L) = C$.

(c) This is obtained by (a) and the fact that every nonzero cyclic submodule in $\text{Rad}(M)$ is a small submodule of $M$ and so cannot be a direct summand. □

4.4. Lemma. Suppose $S$ and $R$ are two rings, $T = R \oplus S$ and $M$ be a $T$-module. Then $M = K \oplus L$ where $K$ and $L$ are modules over $R$ and $S$ respectively. In this case, $Z(M_T) = Z(K_R) \oplus Z(L_S)$ and $\text{Soc}(M_T) = \text{Soc}(K_R) \oplus \text{Soc}(L_S)$.

Proof. Just note that if $M$ is a $T$-module then $M = Me_1 \oplus Me_2$ where $e_1 = 1_R$ and $e_2 = 1_S$ are central orthogonal idempotents in $T$ such that $e_1 S = e_2 R = 0$. Clearly $Me_1$ and $Me_2$ are naturally $R$-module and $S$-module respectively. □

4.5. Theorem. Suppose that $M$ is a nonzero $R$-module and $MI = 0$ for some semiprime ideal $I$ of $R$. If $M \in \text{Cog}(\text{Soc}(M) \oplus R/I)$ and $M/\text{Soc}(M) \in \text{Cog}(R/I)$, then $M_R$ is weakly compressible. The converse holds if $R$ is a right singular semi-Artinian ring such that every cyclic $R$-module has a finitely generated socle or acc on direct summands.

Proof. We may suppose that $I = 0$. Let $N = \text{Soc}(M)$. By Proposition 2.2, $M/N$ is a weakly compressible $R$-module. Hence by Theorem 2.5(f), we need to show that $M$ is $N$-weakly compressible. Assume that $S$ is a simple submodule of $M$, and by hypothesis let $0 : M \hookrightarrow (N \oplus R)^{\lambda} = L$ for some set $\Lambda$. Then $\pi_\lambda \theta(S)$ is nonzero for some canonical projection $\pi_\lambda (\lambda \in \Lambda)$ on $L$. Let $U = \pi_\lambda \theta(S)$ and note that $U \cong S$. Since any minimal right ideal in a semiprime ring $R$ is a direct summand of $R_R$, we deduce that there exists $R$-homomorphism $f : M \to U$ such that $f(S) \neq 0$. It follows $S \not\subseteq \text{Rej}(M, S)$, as desired.

Conversely, suppose that $R$ satisfies the above hypothesis and $M_R$ is weakly compressible. By Theorem 4.1, $M \in \text{Cog}(\text{Soc}(M) \oplus R)$. It remains to show that $M/\text{Soc}(M) \in \text{Cog}(R)$. Since $R$ is assumed to be a semiprime ring, $\text{Soc}(R_R)$ is a direct summand of $R$ by Proposition 4.3(a). It follows that $R \cong A \oplus B$ where $A$ is a semisimple ring and $B$ is a ring with zero socle. By Lemma 4.4, $M = K \oplus L$ and $\text{Soc}(M) = K \oplus \text{Soc}(L)$. Thus it is enough to show that $L/\text{Soc}(L) \in \text{Cog}(B)$. Now $L$ is a weakly compressible $B$-module.

Since $B$ is a right singular semi-Artinian ring, $Z(L)$ has an essential socle, and since $\text{Soc}(B_R) = 0$, every simple $B$-module is singular. Thus $\text{Soc}(L) \leq_{ess} Z(L)$. On the other hand, if $C$ is a cyclic submodule $L_B$, then an application of Proposition 4.3(a) for $C_B$ shows that $\text{Soc}(C)$ is a direct summand of $C$. Hence $\text{Soc}(C)$ is cyclic. It follows that $\text{Soc}(L)$ is a closed submodule of $L$ by Proposition 4.3(b). Therefore $\text{Soc}(L) = Z(L) = Z_2(L)$. The proof is now completed by Lemma 2.1(i). □
4.6. Corollary. Let $R$ be a prime right singular semi-Artinian ring such that cyclic $R$-modules have finite uniform dimensions. Then the following statements hold for $M_R$.

(a) $M \in \text{Cog}(\text{Soc}(M) \oplus R)$ and $M/\text{Soc}(M) \in \text{Cog}(R)$ if and only if $M_R$ is weakly compressible.

(b) $M \in \text{Cog}(\text{Soc}(M) \oplus R)$ if and only if $M_R$ is semiprime.

(c) If $M_R$ is semiprime, then either $M_R$ is semisimple or $Z(M) = \text{Soc}(M)$.

(d) Furthermore, if $R$ is a PID then $M/\text{Soc}(M) \in \text{Cog}(R)$ if and only if $M_R$ is weakly compressible.

Proof. (a) and (b). These follow from Theorems 4.1 and 4.5.

(c). By Proposition 4.3(a), $\text{Soc}(R_R)$ is a direct summand of $R$. Since now $R$ is a prime ring, $R$ is semisimple or $\text{Soc}(R_R) = 0$. If $R$ is a semisimple ring then $M_R$ is semisimple. In case $\text{Soc}(R_R) = 0$, as we see in the proof of Theorem 4.5, $Z(M) = \text{Soc}(M)$.

(d) The sufficiency holds by part (a). Conversely, let $N = \text{Soc}(M)$ and $M/N \in \text{Cog}(R)$. It follows that $Z(M) \subseteq N$ and $M/N$ is weakly compressible. Thus we need to show that $M$ is $N$-weakly compressible. Let $S$ be a simple submodule of $M_R$ and $P = \text{ann}_R(S)$. Let $P = pR$ for some prime element $p \in R$. If $0 \neq x \in S \subseteq MP$, then $x = mp$ for some $m \in M$ and so $p^2R \subseteq \text{ann}_R(m) \subseteq pR$. Hence $p^2R = \text{ann}_R(m)$. This implies that $mR \subseteq N$, a contradiction. Therefore, $S \cap MP = 0$. Since now $M/MP \simeq S^{(\lambda)}$ for some set $\Lambda$, we can deduce that $S \not\subseteq \text{Rej}(M, S)$. The proof is complete. \qed

References


