Deng, Payne, and Hagley Reply: The preceding Comment by Ketterle [1] purports to present a viable model of superradiance in condensates. However, the theoretical framework cited in Ref. [1] cannot explain the red or blue pump laser detuning asymmetry that was first observed recently by us [2]. It is clear from Ref. [3] that rate-equation-based theories are incomplete and only model the final growth stage of the process when a re-detuned pump is used [2]. Our theoretical framework [3], on the other hand, also treats the initial growth stage of superradiance and is therefore also capable of explaining the genesis of the red or blue detuning asymmetry [2]. This is the key message of our response, which we frame in terms of reference to the specific points raised in Ref. [1].

Adiabaticity.—The claim made in Ref. [1] about our assessment of the adiabaticity criteria is incorrect. We simply questioned whether first-order adiabatic elimination used in Refs. [4–6] is adequate for detunings <10^{10} Hz when a fast field relaxation rate of 10^{12} Hz is assumed. In such cases, both spatial and time derivatives of the internally generated field should not be neglected. The argument in Ref. [1] is incorrect in the early stage of a growth process involving spontaneous emission.

Phase matching.—We already acknowledged in Ref. [2] that the phase mismatch relation given in Ref. [3] is not accurate, and we credited the author of the Comment for pointing this out [2]. We note, however, that this phase mismatch relation is not part of, nor does it impact, the theoretical framework of Ref. [3].

Slow velocity.—We do not agree that slow propagation for superradiance has been shown by Refs. [4,5] which discuss a pump-probe Bragg experiment. We note that Ref. [7] explicitly states that the optical fields travel at the speed of light in a vacuum and do not affect scattering at later times. To date, no report prior to Ref. [3] has contradicted that statement [4,6]. Also Refs. [4,5] clearly indicate that the authors believe that the pump-probe (laser-stimulated) and superradiance (spontaneous-emission initiated) experiments are manifestations of different physical processes. In fact, it has been shown [8] that an externally supplied seed laser (probe in Ref. [5]) can easily suppress superradiance, resulting in Bragg diffraction. It is therefore not self-consistent for the author of Ref. [1] to both claim that Ref. [3] does not model superradiance and that Ref. [5] (simple Bragg diffraction) proves the slow propagation of light in superradiance. Finally, Refs. [4,5] only give a generic expression for the group velocity \( v = c(n + adn/da)^{-1} \) to explain the slow wave in the Bragg experiment because these theories are incapable of providing more detail.

Growth mechanism.—It is incorrect to say that Ref. [3], where both detailed atomic response and propagation of the generated field are treated on equal footings, does not have a feedback mechanism that can lead to superradiance. The feedback mechanism and the optical density referred to in Ref. [1] are all properly included in Eqs. (2, 3) of Ref. [3], where at late times in the scattering process the atomic polarization can be viewed as the matter-wave grating described in Ref. [7]. In fact, the lack of superradiant scattering with blue detunings does indeed result from suppression of early-stage growth far from the “high gain” (grating) superradiant threshold. Our analysis is also not predicated on a classical seed field since operator formalism could have been used to describe single-photon seeds from spontaneous scattering. Lastly, the inclusion of linear loss is for completeness only and has no bearing on the conclusion of Ref. [3].

Theory.—The theory described in Refs. [1,4,5,7] has indeed become widely accepted, but it cannot account for recent experimental results [2]. This theory focuses only on the matter-wave grating, and ignores the role of the intranally generated field responsible for the initial growth of matter-wave coherence. Consequently, it is incapable of explaining the observed detuning asymmetry with condensates. Also, Ref. [4] explains superradiance with a simple rate equation plus an argument of Raman time gain based on Fermi’s golden rule. Rate-equation-based theories [4,5] simply cannot predict any propagation dynamics. Equation (1) in Ref. [5] is just a rescaled, single-atom Raman scattering cross section. It is not the coherent propagation gain of Ref. [3]. Although there have been many theoretical studies of superradiance [6], no analytical treatment of field propagation dynamics for collective atomic recoil motion has been reported prior to our work [3].

Conclusion.—Matter-wave superradiance, like optical superradiance, is relatively simple to demonstrate experimentally but difficult to treat theoretically. We emphasize that the widely accepted theoretical framework for superradiance [4,5,7] is fundamentally incapable of explaining the red-blue detuning asymmetry, or any wave propagation effects. Since this framework provides the foundation for many important studies, its revision should be a scientific priority.

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