Reply to "Comment on 'Hadronic production of thermal photons'"

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We address a recent comment by Alam *et al.* [Phys. Rev. C **71**, 059802 (2005)], on our work of thermal photon emission rates from hadronic matter. Specifically, we explain how t-channel ω exchange in the $\pi\rho \to \pi\gamma$ reaction arises as a dominant contribution to the rates at high energy and why hadronic form factors cannot be neglected in this assessment.

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In a recent Comment [1], Alam *et al.* dispute one of our findings in Ref. [2], namely that t-channel ω exchange is a dominant source of high-energy photons from a thermal hadronic gas. In their reasoning, they intentionally omit the insertion of form factors (FFs) at hadronic vertices to "understand the relative importance of ω and a_1 exchange processes" [1].

Hadronic FFs are a conventional way to incorporate finite-size effects in describing hadronic reactions, especially at high momentum transfer, where hadronic substructure becomes important. They arise naturally and are ubiquitous in field theories with emergent degrees of freedom. In Ref. [2] we have calculated photon-generating processes including the exchange of a_1, ρ, and π mesons within the massive Yang-Mills (MYM) approach [3,4], as well as the $\pi\rho\omega$ vertex as given by the Wess-Zumino Lagrangian [5], augmented by standard (dipole) FFs [2,6] that are unity on-shell. The four parameters of the MYM Lagrangian can be fit using measured values [7] of m_ρ, m_{a_1}, $\Gamma_{\rho\to\pi\pi}$, and $\Gamma_{a_1\to\rho\pi}$, whereas the coupling constant $g_{\omega\pi\rho}$ is fixed by the decay $\omega \to \pi\gamma$. The latter is an off-shell decay (proceeding via an intermediate ρ meson) with the FF entering the decay width as $\Gamma_{\omega\to\pi\gamma} \propto (g_{\omega\pi\rho}\, FF_{\omega\pi\rho})^2$. We obtained $g_{\omega\pi\rho} = 22.6\ \text{GeV}^{-1}$ (with a typical FF cutoff of 1 GeV), as compared to $g_{\omega\pi\rho} = 11.93\ \text{GeV}^{-1}$ with $FF_{\omega\pi\rho} \equiv 1$. The presence of the FF clearly and simply increases the coupling constant. Our procedure is corroborated by inspecting the triple-pion ω decay channel. In the gauged Wess-Zumino Lagrangian [5] that reproduces the radiative decay of the ω, the width for $\omega \to \pi\pi\pi$ is $\Gamma_{\omega\to\pi\pi\pi} = 5.1$ MeV (with $FF = 1$), whereas the experimental result is 7.49 ± 0.08 MeV. Once the FF is implemented at each vertex of the reaction, we find $\Gamma_{\omega\to\pi\pi\pi} = 7.47$ MeV. The presence of the FF obviously increases the value of the coupling constant $g_{\omega\pi\rho}$, but of course the full effect has to involve both coupling and FF. The net effect is an increase of the width for $\omega \to \pi\pi\pi$ and this enhancement carries over to the $\pi + \rho \to \pi + \gamma$ reaction with ω exchange.

As discussed in Ref. [2], for the case of ω exchange an incoherent addition of the s- and t-channel contributions is justified. This is illustrated in the top panel of Fig. 1: Adding the pertinent amplitudes coherently (long-dashed line) or incoherently (dotted line) gives essentially identical results. Then, it is possible to absorb the ω s channel in the in-medium ρ spectral function [8], and add the t channel

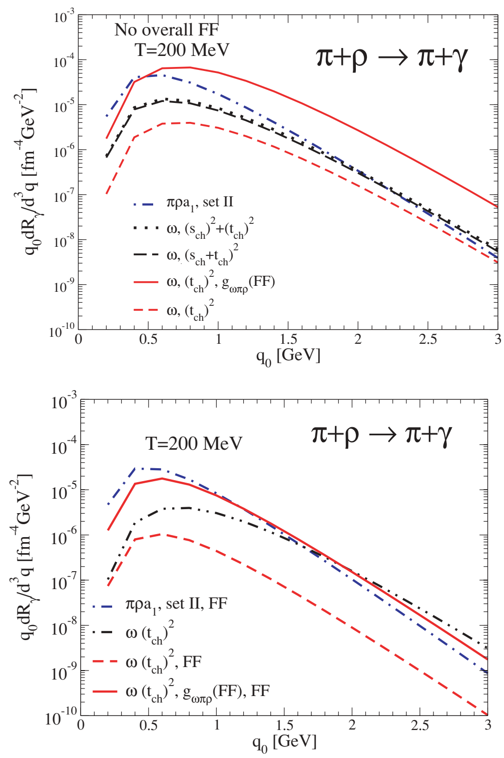

FIG. 1. (Color online) (Top) $\pi + \rho \to \pi + \gamma$ reactions at $T = 200$ MeV without the inclusion of hadronic vertex form factors for the coherent exchange of a_1, π, and ρ (dot-dashed line), ω t channel with $g_{\omega\pi\rho}$ fixed without FF (short-dashed line), ω t channel with $g_{\omega\pi\rho}$ fixed with FF (solid line), and ω diagrams added coherently (long-dashed line) and incoherently (dotted line). (Bottom) Effects of an overall FF. The different channels shown are coherent exchange of a_1, π, and ρ (dot-dashed line) and the t-channel ω exchange with an overall FF: for the case where the coupling is fitted consistently with a FF (solid line) and the case where the coupling is obtained without a FF (dashed line). The t-channel contribution with all FFs consistently set to unity is also shown (dashed double-dotted line).

separately, as has been done in Ref. [2] as a matter of convenience. We have verified that in cases were interference is important, all contributions have been added coherently without double-counting in in-medium ρ spectral densities.

The top panel of Fig. 1 furthermore shows that when $g_{\omega\pi\rho}$ is fixed without FF (short-dashed line), ω t-channel exchange is not the prevalent contribution at high energy. When the larger value of $g_{\omega\pi\rho}$ is employed (solid line), ω t-channel exchange (without FF) is substantially enhanced. However, as argued here, a complete calculation requires a consistent treatment of FFs, not only in the fits for coupling constants. The pertinent results are summarized in the bottom panel of Fig. 1: Both ω exchange and other $\pi\rho a_1$ contributions are reduced, but the former (solid line) becomes dominant at high energy. This is partly due to the fact that the exchanged four-momenta in the (a_1) s channel and the (ω) t channel are quite different (larger in the first case), and thus their relative contributions are sensitive to FF effects.

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