Reply to "Lifetime broadening in bulk photoemission spectroscopy"

Y. Hwu, L. Lozzi, S. La Rosa, and M. Onellion
Department of Physics, University of Wisconsin, Madison, Wisconsin 53706

P. Alméras, F. Gozzo, F. Lévy, H. Berger, and G. Margaritondo
Institut de Physique Appliquée, Ecole Polytechnique Fédérale, CH-1015 Lausanne, Switzerland
(Received 22 September 1992)

The comment by Starnberg, Brauer, and Nilsson qualitatively identifies the final-state lifetime as the cause of the "anomalous" photoemission broadening, but it neglects the linear energy dependence of the final-state broadening whose effect is of the same magnitude as the purely geometrical contributions.

The comment of Starnberg *et al.*[1] is an important step towards the clarification of the "anamalous" broadening in photoemission. We note that no controversy exists about the fundamental point of our previous work (Ref. 2): photoemission linewidths cannot be automatically explained in terms of (initial-state) lifetime broadening, as has often been done in the case of high-temperature superconductors. Starnberg, Brauer, and Nilsson explicitly agree with this central conclusion.

The main point in Ref. 1 is that final-state broadening plays an important role in the case of their data as well as our data on silver. This is not a new conclusion: it has already been discussed, unfortunately in an unpublished form, by Smith, Thiry, and Petroff.[3] After considering their results as well as those of Ref. 1, we agree that the *qualitative* energy dependence of our Ag (100) data can be explained by final-state broadening. However, the treatment by Starnberg, Brauer, and Nilsson[1] neglects one important cause of this dependence: the changes with energy of the final-state broadening. The point is potentially misleading for the reader, and therefore it must be clarified together with two other points that play an important role in photoemission broadening.

The model of Ref. 1 assumes an *energy-independent* final-state broadening, whereas the broadening is expected to increase linearly in the range of interest.[3,4] Without taking this factor into account, the "anomalous" energy dependence of the linewidth would appear to be primarily caused by the angular dependence of the weighting factor of the final-state lifetime broadening. But this is misleading, since the two contributions to the energy dependence have approximately the same magnitude.[3] A quantitative treatment of the lifetime broadening must, therefore, take into account both of them.

Also note that a complete analysis should take into account the effects of the finite angular acceptance of the analyzer—which, for example, as we pointed out in Ref. 2, explain the line-shape asymmetry. This point has been analyzed by Becker *et al.*,[5] who derived an energy-dependence contribution qualitatively similar to the "anomalous" one, and whose magnitude appears important.

Finally, we believe that it is potentially dangerous to automatically eliminate from the analysis the initial-state contributions to the broadening, in particular, when the perpendicular group velocity in the final state is small. The most general approach must be based on the Smith-Thiry-Petroff[3,6] expression [of which Eq. (3) in the comment of Starnberg, Brauer, and Nilsson[1] is an approximation]:

$$\Gamma_m=(\Gamma_i/|v_{i\perp}|+\Gamma_f/|v_{f\perp}|)[(1/v_{\perp})(1-2\pi m v_{i\parallel}\sin^2\theta/hk_{\parallel})-(1/v_{f\perp})(1-2\pi m v_{f\parallel}^2\sin^2\theta/hk_{\parallel})]^{-1},$$

where Γ_m, Γ_i, and Γ_f are the total, initial-state, and final-state broadening, the v's are the group velocities, and the other symbols correspond to those of Ref. 1.

This general equation can be reduced to a single type of contribution if either Γ_i or Γ_f is much larger than the other broadening, or one of the group velocities is very small. It should be strongly emphasized that this latter condition is *not* automatically presented for layer compounds like the high-temperature superconductors, since, as it has been correctly pointed out in Ref. 1, the perpendicular dispersion can be large notwithstanding the two-dimensional character of the crystal structure.

In conclusion, the analysis of Starnberg, Brauer, and Nilsson,[1] complemented with the points discussed above, corroborates the conclusion that an "anomalous", i.e., nonquadratic or even decreasing rather than increasing, energy dependence of the photoemission linewidth cannot be taken as evidence of non-Fermi-liquid behavior. This, we believe, is a fundamental point as far as photoemission and the nature of high-temperature superconductors are concerned.

We are grateful to Neville Smith, Yves Petroff, and Eberhardt Dietz for the excellent discussions we had on their work and for having disclosed to us some of their unpublished results. This work is supported by the Fonds National Suisse de la Recherche Scientifique, by the U.S. National Science Foundation (directly and through the Wisconsin Synchroton Radiation Center), and by the Ecole Polytechnique Fédérale de Lausanne.

[1]H. I. Starnberg, H. E. Brauer, and P. O. Nilsson, preceding paper, Phys. Rev. B **48**, 621 (1993).
[2]Y. Hwu, L. Lozzi, S. La Rosa, M. Onellion, P. Alméras, F. Gozzo, F. Lévy, H. Berger, and G. Margaritondo, Phys. Rev. B **45**, 5438 (1989).
[3]N. V. Smith, P. Thiry, and Y. Petroff (unpublished); (private communication).
[4]A. Goldmann, W. Altmann, and V. Dose, Solid State Commun. **79**, 511 (1991).
[5]H. Becker, E. Dietz, U. Gerhardt, and H. Angermüller, Phys. Rev. B **12**, 2084 (1975).
[6]Note that such result has been explicitely obtained by P. Thiry, Ph.D. thesis, Université de Paris-Sud, 1981 (unpublished); a partial derivation had been presented by T.-C. Chiang, J. A. Knapp, M. Aono, and D. E. Eastman, Phys. Rev. B **21**, 3513 (1980).